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# FEATURES OF EXPLOSION WELDING OF ODS STEEL FOR FAST NEUTRON REACTOR SHELLS

**P.S. Shlonskyi, Feng Gao**

Liaoning Xin Huayang Weiye Equipment Manufacturing Company Ltd No. 1 Road, Tieling high-tech industrial development zone, Liaoning province, China

**ABSTRACT**

The paper investigates the possibility of explosion welding of plates and disks made of dispersion-strengthened low-plastic steel with oxides. In order to prevent the appearance of cracks on the surface of the plates, low-temperature (up to 200 °C) heating was applied to the flyer plate. In a wide range of explosion welding parameters with reference to the weldability window (WW), the microstructure of the resulting joint is shown for 2 mm thick and 50 diameter discs, that were laser welded into carbon and stainless steel plates. A tensile strength test was conducted for the obtained joints, it was possible to achieve a joint strength of 75 % of the strength of the base metal. Explosion welding of 100×50×3 mm plates was performed, the border of the joint zone has a typical wavy shape for explosion welding. Using energy dispersive X-ray spectroscopy, the chemical composition of inclusions in the joint zone was determined, and it was established that silicates are present in the joint zone. It is shown that the application of low-temperature heating allows welding plates from ODS steel with the help of explosion energy.

**KEYWORDS:** ODS-steel, explosion welding, weldability window, low-temperature heating, microstructure

## INTRODUCTION

A distinctive feature of nuclear energy has always been the need for new structural materials for nuclear power plants.

Nanotechnology has been used in this field since before the prefix "nano" was used, since the created fuel and structural materials were largely based on a qualitative change in the properties of materials during the transition to the nanometric size range [1, 2].

The areas of application of nanotechnology in nuclear power are very diverse and cover almost the entire range of problems of the nuclear fuel cycle and the emerging fusion cycle. One of them is the creation of nanodispersed materials for structural and functional purposes, namely, ferritic-martensitic steels or nanodispersed ODS steels. The basis of such steel is Eurofer powder, to which tenths of a mass percentage of $Y_2O_3$ are added [3].

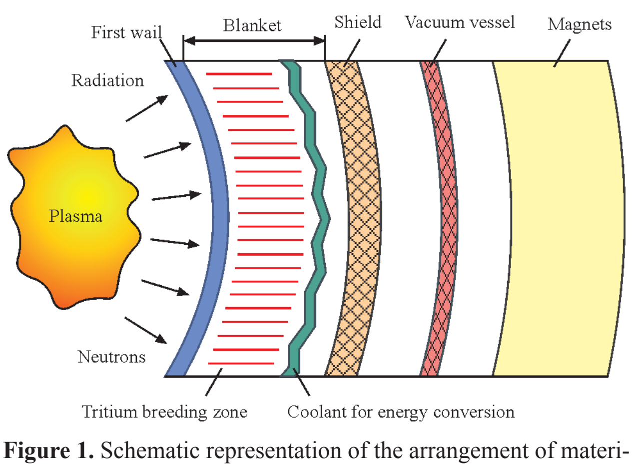


**Figure 1.** Schematic representation of the arrangement of materials in a tokamak [6]



Ferritic-martensitic steels are the main candidates for modern materials for fast reactor pressure vessels due to their satisfactory resistance to radiation and radiation swelling (with high-temperature irradiation by large neutron fluxes in austenitic steels and alloys based on Ni, Ti, Mo, Zr, Be, vacancy pores originate and grow, and mobile interstitial atoms move to edge dislocations and grain boundaries, which leads to a noticeable increase of the volume of metal — radiation swelling [4]). However, these steels can suffer from grain and/or matrix creep at temperatures above 550 °C.

To achieve the goal of operating innovative reactor systems at higher temperatures, it is necessary to consider the use of ODS steels. It is possible to use these steels for the blanket (Figure 1), which will increase the operating temperature to ~850 °C [3, 5, 6]. The blanket is a very thermally and radiation-intensive system of the international thermonuclear reactor — ITER, its purpose is to capture high-energy neutrons produced during a thermonuclear reaction, in it the neutrons are slowed down, releasing heat, which is removed by the cooling system.

A schematic representation of the arrangement of materials in a thermonuclear reactor is shown in Figure 1.

Evaluation of various (conventional and alternative) production methods, studies of mechanical properties and material degradation due to irradiation are widely carried out both in China and around the world (USA, Japan, Europe Union, Ukraine). Another pressing issue for ODS steels is the development methods for their inseparable connection by welding.. It is known that welding processes can adversely change the microstructure and, consequently, the mechanical properties of the base material. Therefore, understanding the microstructural changes caused by weld-

**Table 1.** Chemical components of ODS-steel(s)

| Alloy | C | Si | Mn | Cr | V | W | Ta | $Y_2O_3$ |
|---|---|---|---|---|---|---|---|---|
| Eurofer | 0.12 | 0.06 | 0.42 | 8.87 | 0.19 | 1.1 | 0.14 | 0.3 or 0.5 |
| Other elements weight (%) Nb, Mo, Ni, Cu, Al, Co limited by values ppm. | | | | | | | | |

ing and their impact on mechanical properties, as well as evaluating preventive measures, is of great importance to improve the quality of the received joint.

The joining of ODS steels is a challenging task, as traditional fusion welding processes, such as electron beam welding and non-consumable electrode welding, can not only change the characteristic microstructure of the base material, but also destroy $Y_2O_3$ particles, which can affect to the mechanical characteristics of material's at high temperatures.

The explosion welding (EW) is a process in which there is no need for a heat source, and an indissoluble joint is formed due to the mechanical (kinetic) energy of the impacting plates [7, 8]. Therefore, this method can be classified as "cold", i.e., not requiring heating to the melting point or close to it. The zone of thermal influence during explosion welding under optimal conditions relative to the thickness of the plates to be welded is small and amounts to several tens of micrometers. The duration of high temperatures is also short. This method can be used to join almost any metal and alloy to each other or through a layer of another metal.

Therefore, it is of interest to investigate the possibility of using explosive welding to join ODS steels with an estimate of the weldability window.

An important achievement of the hydrodynamic theory is the introduction of the concept of the WW [9–11]. The first ideas about the position of the weldability window boundaries were developed in the early 1970s. A significant contribution to the study of flow classification in the "$V_c$–γ" coordinate plane was made by A.A. Deribas and colleagues. Within the framework of the hydrodynamic approach, when designing the welding mode, it is necessary to ensure that the trajectory of the working point on the coordinate plane during the explosion welding process does not leave the part of the weldability window that corresponds to the modes of formation of a high-quality joint. The position of the boundaries of the weldability window is individual for each metal combination and is set experimentally.

For materials with low plasticity and high strength, EW with low-temperature heating is widely used in practice [12]. A successful example of such application can be considered the paper [13], which describes the development of the bimetallic composite manufacturing technology "high-speed steel P6M5 + carbon or low-alloy steel" for tool production. The viscous-brittle transition was most clearly determined in impact toughness tests and occurred in the temperature range of 125–175 °C. Therefore, EW of ODS-steel expedient to perform with low-temperature heating up to 200 °C, which will probably increase its plasticity and which is lower than the temperature of complete decomposition of saltpeter (210 °C), the main component of the explosive.

**Table 2.** Mechanical properties ODS-steel(s)

| $\sigma_y$, MPa | $\sigma_t$, MPa | Uniform elongation δ, % | Total elongation δ, % |
|---|---|---|---|
| 1060±45 | 1135±50 | 3.2±0.3 | 12.8±0.9 |

The aim of this work was for the first time in world practice to investigate the fundamental possibility of obtaining a welded joint between ODS steels using low-temperature heated explosion welding, to study its microstructure and strength.

## INVESTIGATION PROCEDURE

For this work, ODS steel, manufactured in the European Union, so-called Eurofer ODS (0.3 wt.% $Y_2O_3$), was used in the form of a hot-rolled sheet of 260×225×3 mm, the size of the cut plates was 100×50 mm. The samples for research were obtained from the rod and had the shape of round discs with a thickness and diameter of 2 and 50 mm, respectively. The chemical composition and mechanical properties of ODS steel are shown in Tables 1 and 2, respectively.

Metallographic studies of the structure of metals after SH were carried out using a metallographic microscope MMO-1600 with a magnification of up to 1600×. The microstructure was photographed with a CMOS camera (KONUS, Italy) with a USB socket.

Since the disks are only 50 mm in diameter, they were welded into stainless steel plates (Figure 2) (throwing disk) and carbon steel (base disk) using la-

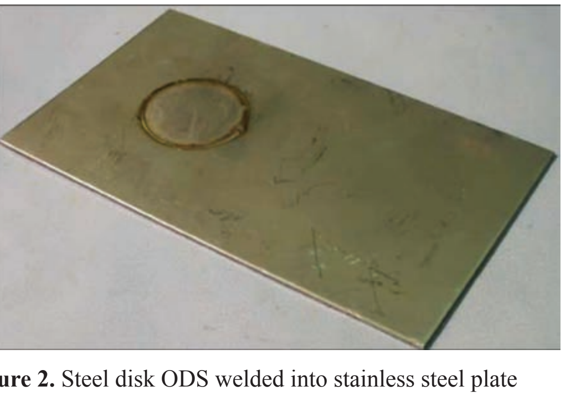

**Figure 2.** Steel disk ODS welded into stainless steel plate

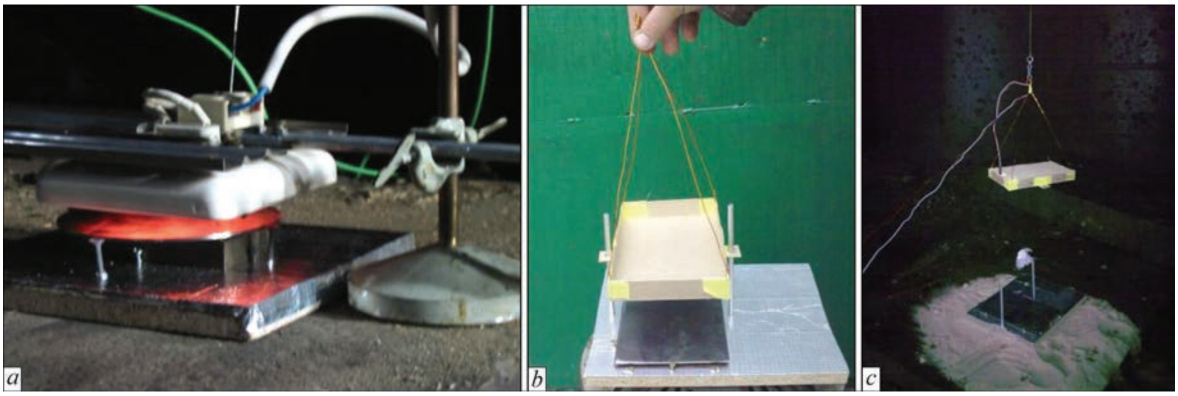


**Figure 3.** Additional operations during EW of the disk from ODS steels with low-temperature heating: *a* — heating; *b* — explosive box with bottom and guides; *c* — box filled with explosive ready for remote installation

ser welding. The discs were welded in order to move the initial and final unbonding zone their limits.

Figure 3 shows photographs of additional operations and devices for the implementation of the technology EW with heating. To heat the plate to be thrown, we used ceramic infrared heaters of the panel type manufactured by the German company Elstein (Figure 3, *a*). The temperature on the surface of the plate was measured using a four-channel thermometer Voltcraft K204 (measuring range from –200 to +1370 °C) with a K-type thermocouple.

In order to reduce the time for the formation of the charge, the box for the explosive substance was made with the bottom of Figure 3, *b*. That made it possible to pour the explosive powder into the box in advance and, after heating, quickly install it on the surface of the plate that is thrown. Guide rods were installed on the sides of the plates to be welded, and wings with holes were attached to the sides of the box (Figure 3, *b*), so the centering of the charge relative to the plates was ensured remotely. In Figure 3, *c* shows a cardboard box filled with an explosive and a detonator, which will be remotely lowered onto the plates which will be welded.

In order to determine the weldability range of ODS steel, experiments were conducted with the following initial angles α between the plates: –2.00°, 0.00°, +2.00° and +4.00° and the corresponding contact point velocities $V_c$ (welding): 3881.00 m·s$^{-1}$, 2875.00 m·s$^{-1}$, 2290 m·s$^{-1}$ and 1904.00 m·s$^{-1}$. The welding gap was 4.8 mm. The plates with welded ODS-steel disks after WW are shown in Figure 4. A defect in the form of a crack, which can be observed in Figure 4, this is not a EW defect, the ODS-steel disks are welded together well, the delamination occurred in the laser welding zone.

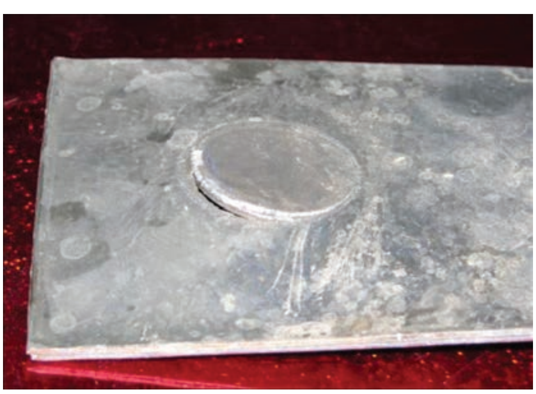

**Figure 4.** Plate welded with disks made of ODS-steel after EW

## RESULTS AND DISCUSSION

After explosion welding, the samples were subjected to metallographic studies. The microstructure of the ODS-steel joint zone at different modes with reference to the weldability window (WW) is shown in Figure 5.

The left part of the weldability window is represented by the microstructure image Nos 1, 2. Very large strain shifts are observed there, either with almost no waves in No. 1 or with long waves at the interface between the ODS steel disks No. 2.

Regular waves with an amplitude of approximately 100 μm and the absence of melts in the image of microstructure No. 3 indicate that it is in this regime that the best conditions for the EW ofODS-steel are realized.

In the image of microstructure No. 4, you can see that the wave amplitude becomes smaller compared to No. 3. This is because the velocity of the impact point has increased to approximately 4000.00 m/s. Therefore, due to the heat generated at high welding speeds, vortices, the so-called “pockets”, begin to form.

Thus, it can be said that the optimal detonation speed for welding ODS steel is 2875 m·s$^{-1}$, and the welding gap is 4.8 mm, which provides a impact velocity of about 750 m·s$^{-1}$.

In the image of microstructure No. 4, you can see the marks after measuring the microhardness near the joint zone and in the “pockets”. However, the microhardness values are close: 440 *HV* near the interface and 420 *HV* in the “pockets”.

After conducting research on samples with disks, plates made of ODS steel measuring 100×50×3 mm were welded. Welding was performed with heating up to 200 °C, the welding mode was as follows: welding gap — 4 mm; explosive mixture of Ammonite 6ZhV

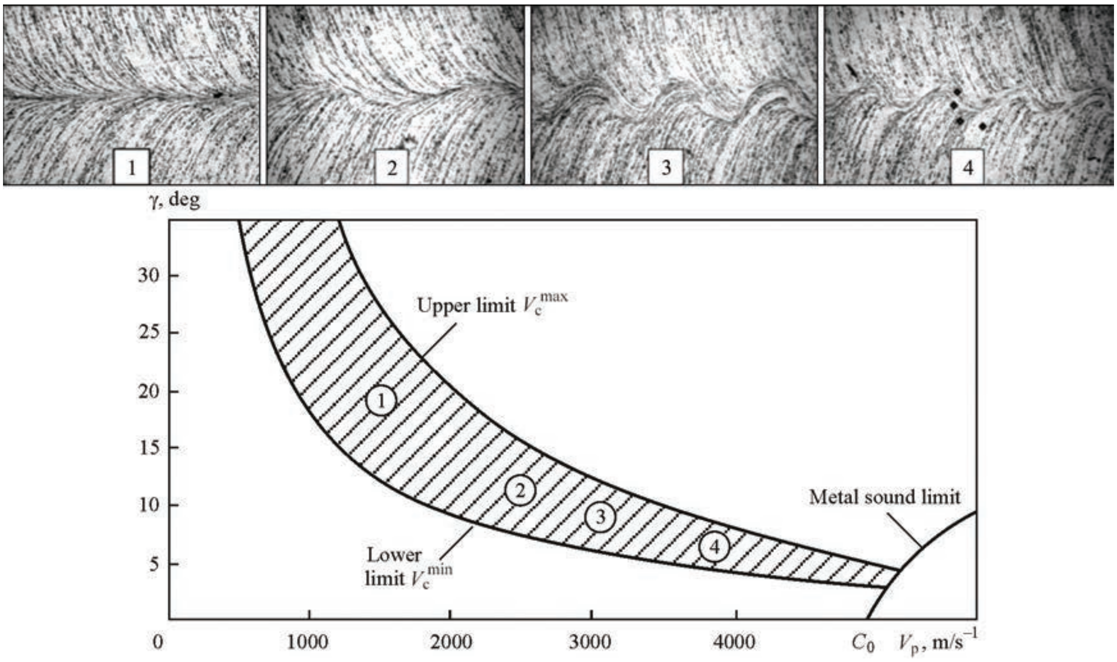


**Figure 5.** Microstructure of the welding zone of ODS-steel disks under different welding modes (*a*) with reference to the WE (*b*). 1 — α = + 4,00°, $V_c$ = 1904.00 m·s$^{-1}$; 2 — α = +2°, $V_c$ = 2290 m·s$^{-1}$; 3 — α = 0.00°, $V_c$ = 2875 m·s$^{-1}$; 4 — α = –2°, $V_c$ = 3881.00 m·s$^{-1}$

with sand 60 %/40 %. As a result, it was possible to successfully weld the plates together and obtain the sample shown in Figure 6. A section was cut out of the obtained sample to study the microstructure of the joint zone. The image of the ODS-steel + ODS-steel microstructure is shown in Figure 7.

After etching, the cross-section of the sample has a typical wavy shape at the interface and light inclusions (indicated by red arrows). Energy dispersive X-ray spectroscopy (EDX) of Figure 8 showed that these inclusions are silicates, Table 3. The locations of the EDX analysis are indicated by arrows and numbers.

A possible explanation for the presence of silicates on the surface between the plates is that due to the short length of the plates to be welded, complete cleaning of the surfaces by the cumulative jet did not occur. Studying the effect of these inclusions on the mechanical properties of the material welded by the blast and the presence of silicates in subsequent samples is of interest for further research.

Since EW of ODS steel is performed with low-temperature heating, it is interesting to theoretically estimate the temperature that will be in the zone of joint formation and test its tensile strength.

During EW, the metal layers adjacent to the contact surface are heated by several mechanism [8]:

● large plastic shear deformations of the surface layers;

● capture of the cumulative flow (the so-called “back jet”) during welding in the mode with the formation of waves [7, 14];

● heating from shock compressed air in the welding gap.

In our case, the first two mechanisms are essential, since the length of the workpieces is short.

The degree of heating depends on the choice of the EW mode. Heating from shear deformations is always present, but in the case of EW with wave formation, its intensity is increased due to the presence of the tangential component $V_t$ of the velocity of surface contact. The larger $V_t$, the greater

**Figure 6.** Sample of the ODS-steel + ODS-steel obtained by EW

**Figure 7.** The microstructure of the EW zone of ODS-steel plates

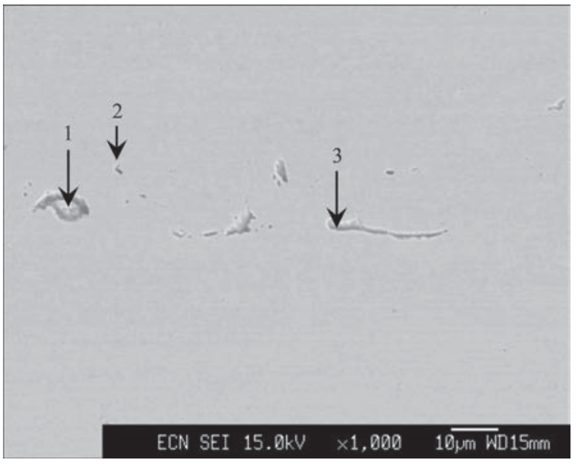


**Figure 8.** The locations of EDX analysis are indicated by arrows and numbers

the shear deformation and heating. Therefore, the magnitude of the $V_t$ component and the heating intensity change cyclically with a period equal to the wavelength.

Plastic shear deformations due to $V_t$ and the capture of cumulative flow are responsible for the formation of melts in the so-called "pockets". The volume of the vortex zone content increases as the mode moves away from the lower boundary of the WW, and as it approaches the upper boundary, the melts can form a continuous layer, which deprives the joint of strength. At the same time, the greater the relative elongation of the weld gap (the ratio of its length to width), the greater the proportion of the cumulative flow that is trapped in the vortex zone. In our case (ODS + ODS), there are no clearly defined vortices yet, but the micrographs already show quite significant melt zones (light) Figure 7.

At present, there are no methods for engineering calculation of thermal fields at the EW (especially in the mode with wave formation). There is a known technique for the experimental determination of thermal fields, which requires measurements of plastic deformation fields in samples taken from metal layers. This technique, developed at the Volgograd State Technical University, is cumbersome and expensive, and is rarely used.

The existing understanding of the heating intensity in the modes of explosive welding used in our experiments is as follows. The plates to be welded can be conditionally divided into three zones by thickness:

- a formation zone of bonding (FZB) adjacent to the contact surface, the thickness of which is assumed to be equal to the amplitude of the welding waves;
- a transition zone of the same thickness order as the FZB;
- the main layer of the plate.

The thickness of the first two zones combined is an order of magnitude less than the thickness of the plates to be welded (in our case, they occupy approximately 12–15 % of the thickness). The main volume of the plate is heated by tens of degrees Celsius during the EW process. The temperature field equalization in the welded sample generally takes tens of microseconds. The temperature of the throwing plate and the contact zone after alignment can reach 100 °C, provided there is no preheating.

**Table 3.** Results of EDX analyses of the inclusions

| Location | Chemical composition, wt.% | | | | | | |
|---|---|---|---|---|---|---|---|
| | W | Si | Ca | V | Cr | Mn | Fe |
| Base metal | 1.0 | 0.1 | – | 0.2 | 9.3 | 0.6 | 88.8 |
| Point 1 | 0.9 | 0.3 | – | – | 9.7 | – | 89.1 |
| Point 2 | – | 4.6 | – | 0.7 | 13.1 | – | 81.6 |
| Point 3 | – | 7.1 | 0.5 | – | 9.0 | – | 83.3 |

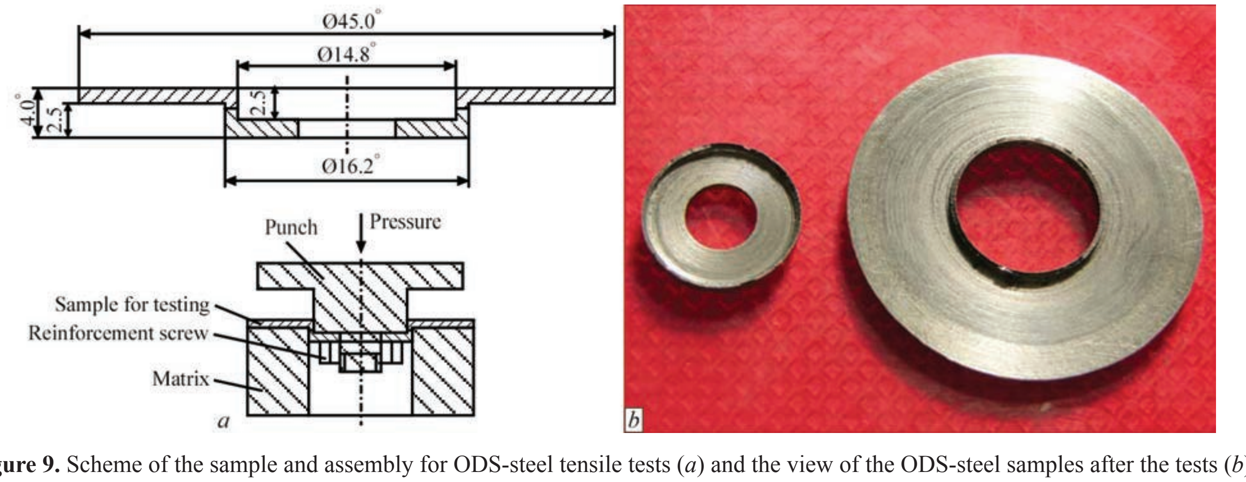


**Figure 9.** Scheme of the sample and assembly for ODS-steel tensile tests (*a*) and the view of the ODS-steel samples after the tests (*b*)

The temperature of the joint formation zone reaches its maximum on the contact surface. In our case, in some areas of the contact surface, it reaches the melting point. The average temperature of the joint formation zone for ordinary metals can be 550–750 °C. In our case of a high-strength metal and rather high velocities of plate throwing (750 m/s) and detonation (2850 m/s), it is likely to be 800–900 °C.

The maximum temperature reached in the transition zone varies with its thickness for ordinary metals in the range from 100 to 200–400 °C, in our case, possibly to a higher temperature.

Thus, it can be assumed that preheating to 200 °C of ODS steel plates to be welded by explosion will not have a significant impact on their mechanical properties after EW.

Tensile strength tests were performed for ODS steels welded by explosion according to the scheme shown in Figure 9, *a*, *b* shows a sample after tear tests. The tensile strength for ODS steels welded by explosion in mode 3 was 851 MPa.

## CONCLUSIONS

1. The research and development work carried out has shown that explosive welding of ODS steel to an ODS disk has a wide weldability window within the contact point speed range of 2000.00 to 4000.00 m/s. The highest joint strength achieved for ODS steel is 75 % of the strength of the base metal.

2. The extremely high strength and low ductility of ODS-steel requires preliminary low-temperature heating (up to 200 °C) of the plate that is thrown, as well as the use of welding modes with an increased speed of the contact point, compared with ordinary steels.

3. The structure of ODS-steel is quite attractive for the study of high-speed deformation and the mechanism of explosion welding, so the development of further research and development work looks quite interesting and perspective.

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**ORCID**

P.S. Shlonskyi: 0000-0002-3566-1752

**CONFLICT OF INTEREST**

The Authors declare no conflict of interest

**CORRESPONDING AUTHOR**

P.S. Shlonskyi
Liaoning Xin Huayang Weiye Equipment Manufacturing Company Ltd No. 1 Road, Tieling high-tech industrial development zone, Liaoning province, China.
E-mail: shlensk@ukr.net

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