EXPERIMENTAL EVIDENCE FOR FORMATION OF SHOCK PLASMA DURING EXPLOSIVE WELDING

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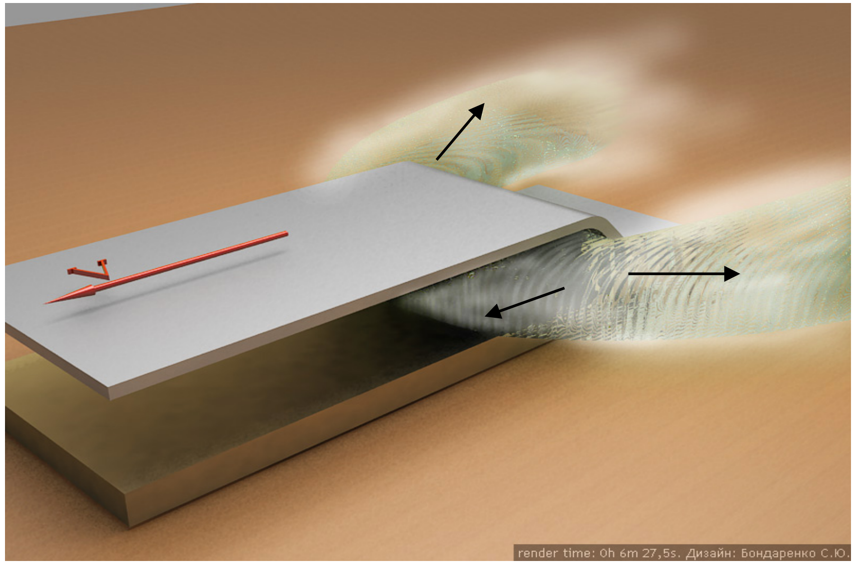
Three main models interpreting compound formation during explosion welding

- A model based on the laws of hydrodynamics describing collision of two jets of an ideal incompressible fluid angularly. The research formed the basis for the explosion welding theory and allowed one to define the basic parameters of the process.

- A model based on the classical theory of pressure welding in the solid phase. Developed were explosion welding mechanisms taking into account presence of intensive plastic deformation in the contact zone.

- A model based on aerodynamic heating impact on welding surfaces by shock-compressed gas ahead of the contact point during its flow at hypersonic velocity

- In [1, 2] and EPNM reports [3, 4], it was hypothesized that thermal gas ionization occurs on the interface (boundary layer) in the stand-off gap ahead the contact point when hypersonic flow (Mach 5-8) of 2700°C heated shock-compressed gas interacts the sheets and thin layers of low-temperature shock plasma are formed [5] .



References

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2. L.B. Pervukhin, O.L. Pervukhina, S.Yu. Bondarenko, Cleaning and activation of welded surfaces during explosion welding, Paton Welding J., 2010, no. 7, pp. 41–43.
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Research technique

1. For sheets (2000x13000 mm) theoretically determined

   - parameters of shock-compressed gas in the welding gap ahead of the contact point
   - time and results of shock-compressed gas impact on the surface to be welded.

2. Carbon steel + AISI 321 sheets (30 x2000x12900 mm) were produced and estimated with ultrasonic defectoscopy and tensile strength testing.

   Templates (100x1450 mm) were cut along the full length of the sheet.

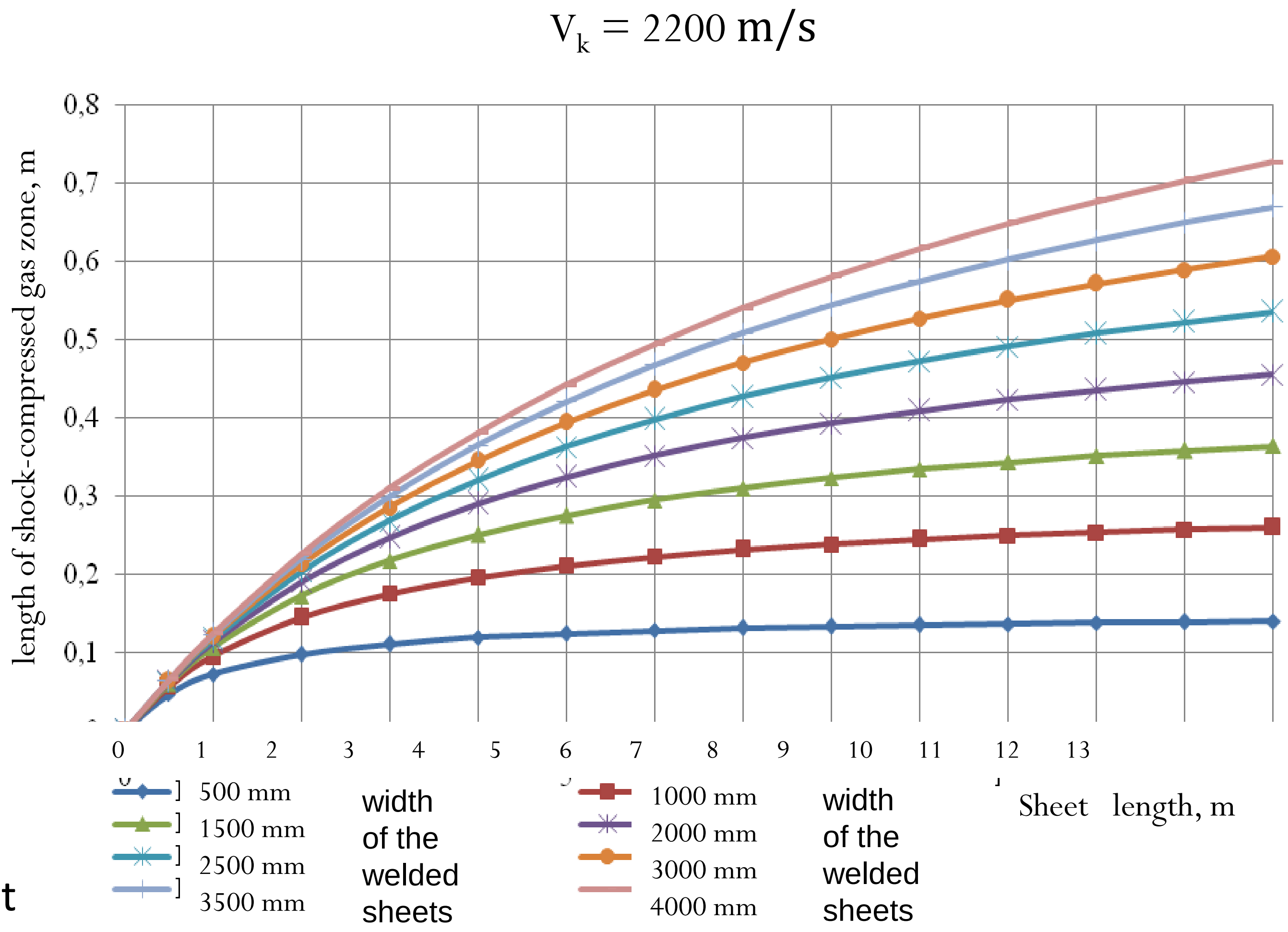
3. - Studied structures in the quality and defect zones:
   - Measured wave sizes along the sheet and cast inclusions amount, studied structure and chemical composition by EDS analysis
   - tested changes of tensile strength

Size of shock-compressed gas zone

$$l = f(s)$$

$$l = \frac{s\rho_0 b}{\rho_1 b + 2\frac{s}{v_\kappa}\sqrt{\frac{2\gamma}{\gamma+1}P_1\rho_1\left(\frac{2}{\gamma+1}\right)^{\frac{2}{\gamma-1}}}}$$

ρ_0 – density of flowing gas, b – length of the contact line, P_1 – pressure in the shock-compressed gas, $V\kappa$ – contact point velocity, υ - velocity of the gas, l - length of shock-compressed gas zone, s – distance from the contact point

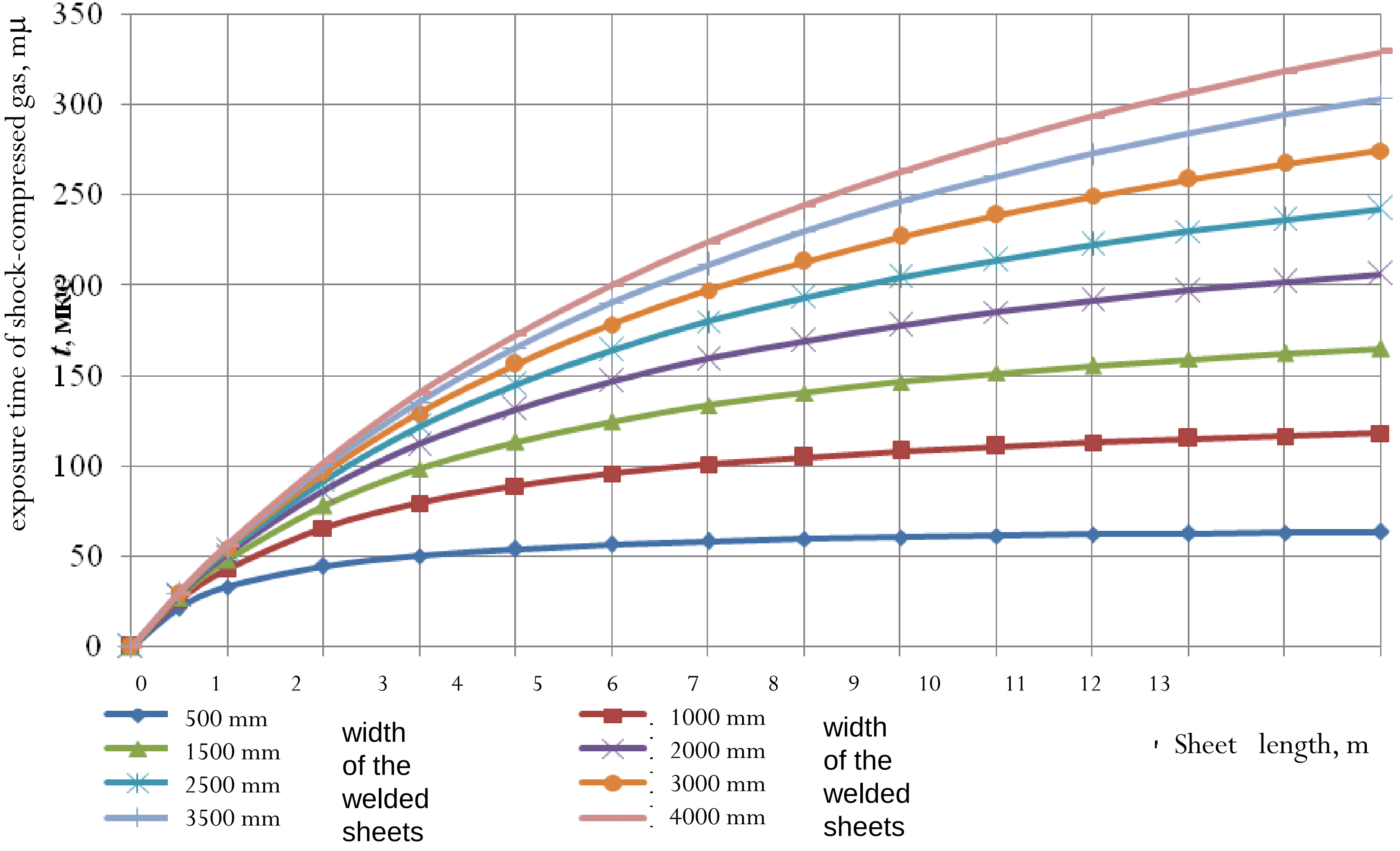


*S.Yu. Bondarenko, O.L. Pervukhina., D.V. Rikhter, L. B. Pervukhin, Determination of the parameters of shock-compressed gas in the welding gap ahead of the contact point in explosion cladding, Paton Welding J., 2009, no. 11, pp. 39–41.

Dependence of exposure time of shock-compressed gas on length and width of the sheet

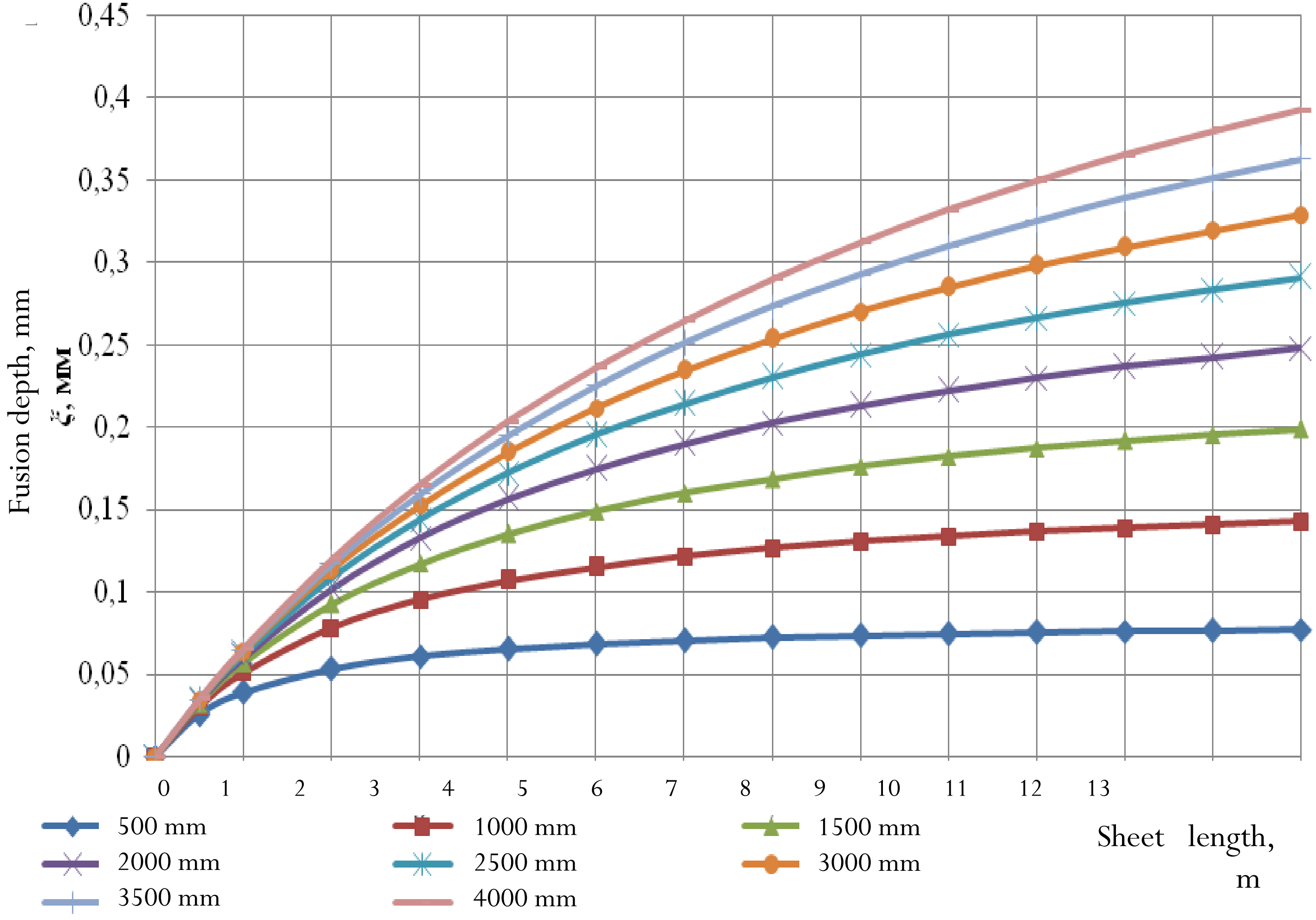
$$t = \frac{l}{V_k}$$

$V_k = 2200$ m/s



Determination of the fusion depth of material to be welded

$$\xi = \xi_{пл} + \xi_{осн}$$



$$\xi = \frac{q \cdot t}{\rho_{Me} \cdot r_{Me}},$$

q – heat flow of gas into the metal;

ρ_{Me} and r_{Me} – the density of the metal and the heat of sion.

$$q = St \cdot \rho_г \cdot u \cdot C_p \cdot (T_e - T_0)$$

q – heat flow of gas into the metal;
St – Stanton number;
C_p; $\rho_г$ – heat capacity and density of the gas;
u – the mass velocity of the gas behind the shock front;
T_e – reduction temperature;
T_0 – the initial temperature of the metal wall (273 K).

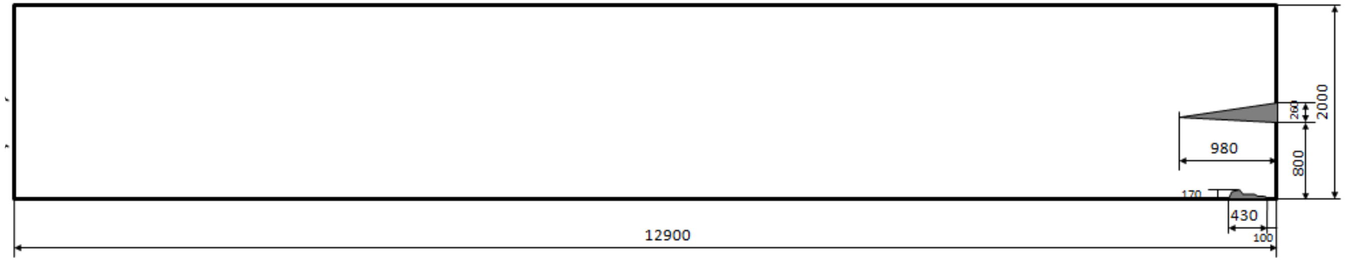
$$St_T = \frac{1}{8\left(2\lg\frac{a_p}{k} + 1{,}74\right)^2}$$

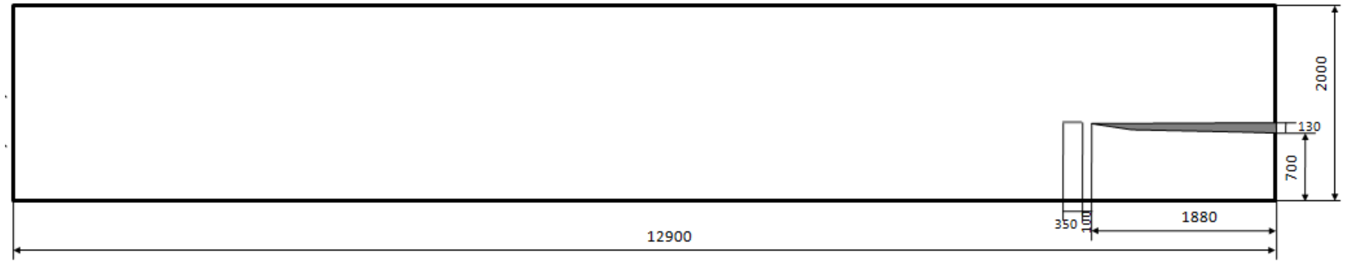
a_p – the distance between the plates;
k – the average size of surface roughness.

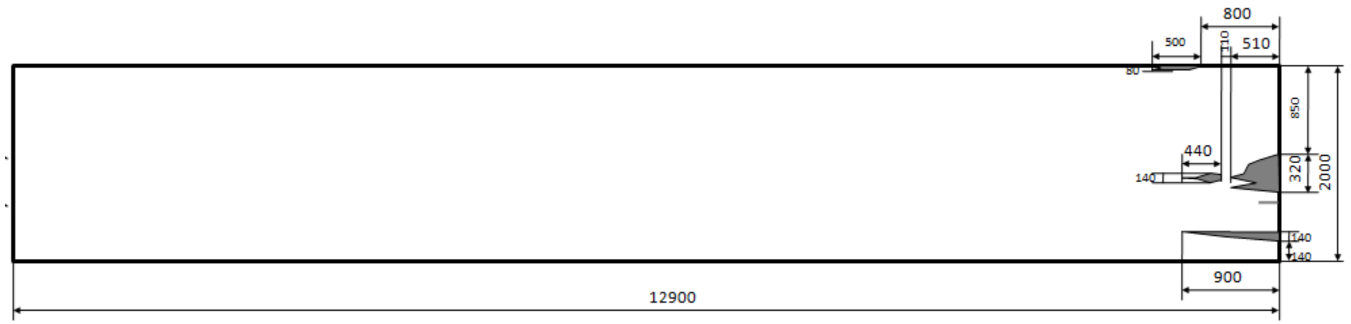
$$T_e = T_{УСГ} \cdot \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)$$

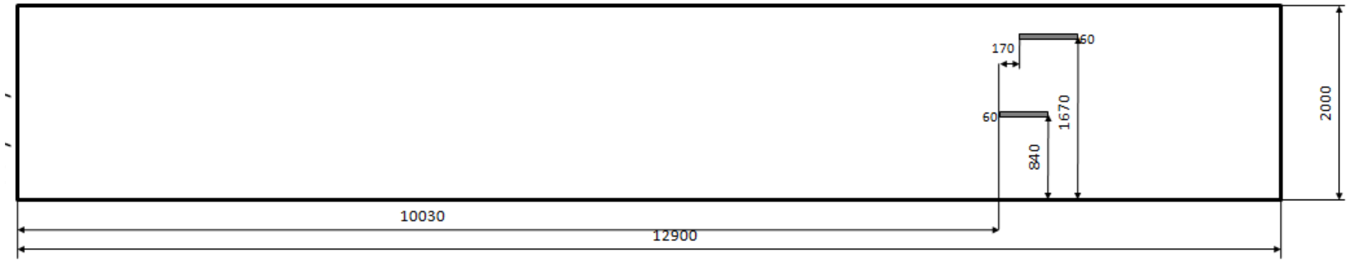
$T_{УСГ}$ – the temperature of the shock-compressed gas;
M – Mach number;
γ – adiabatic index

Experiments and results of ultrasonic testing

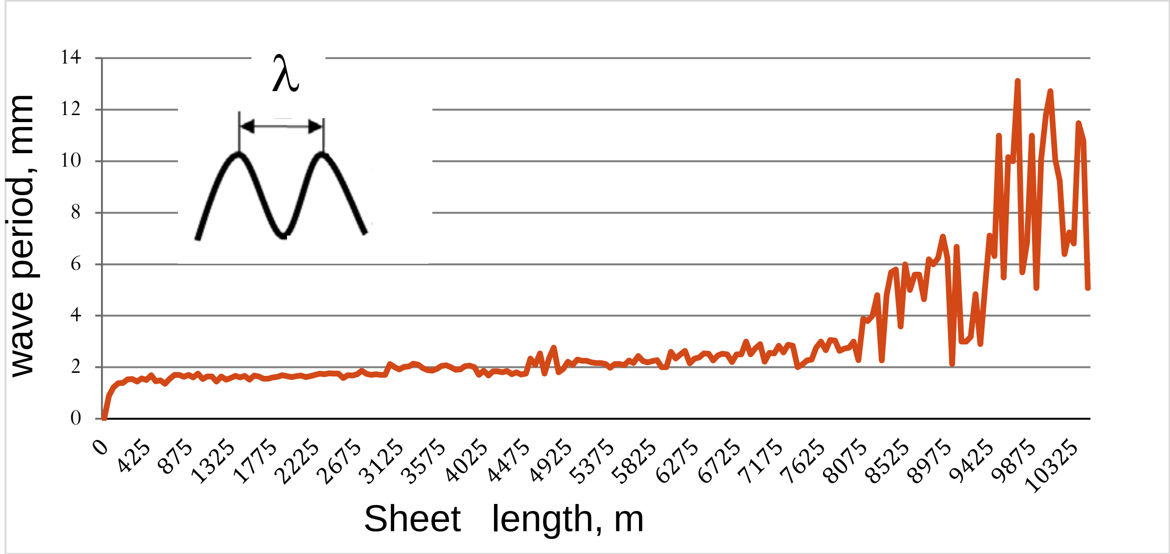


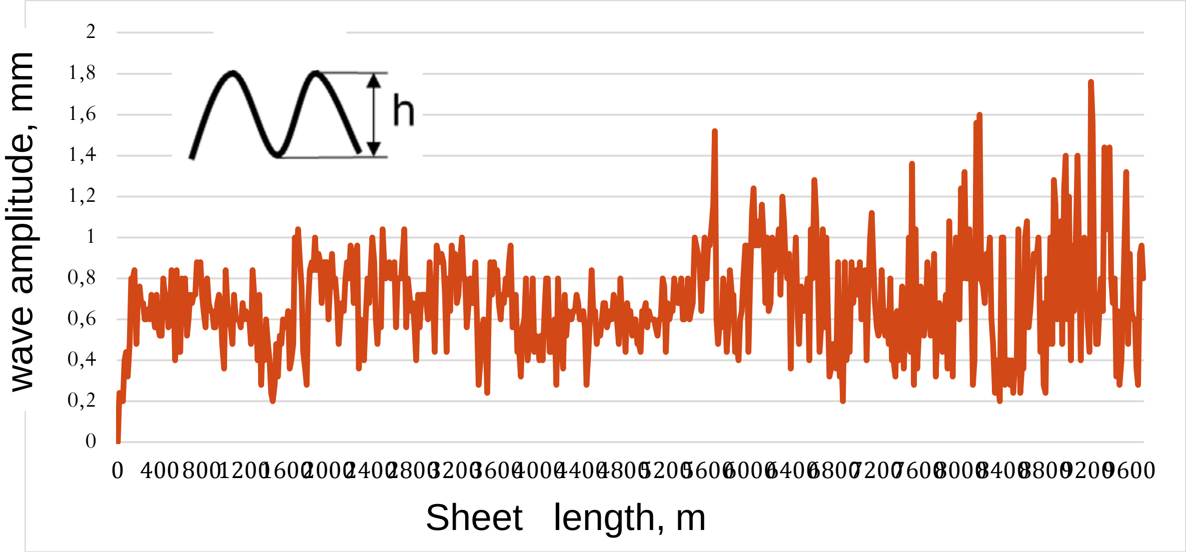


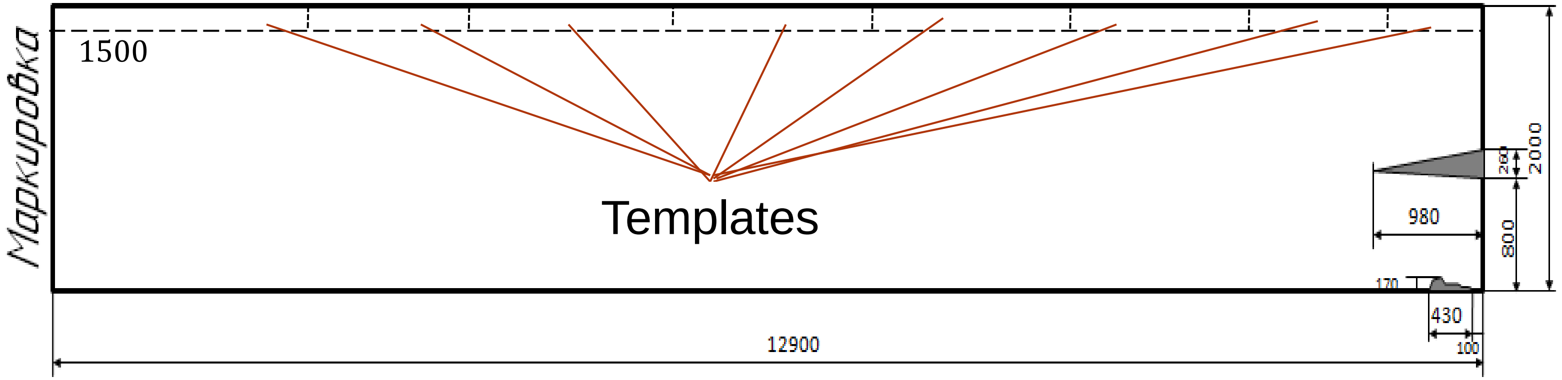




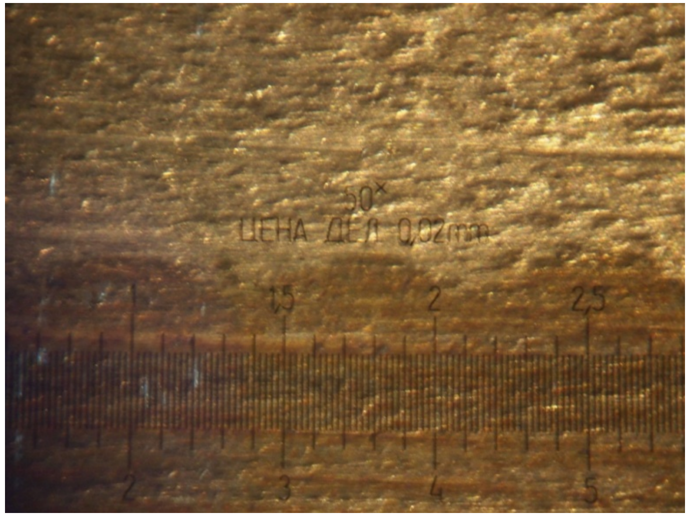
The study of wave structure



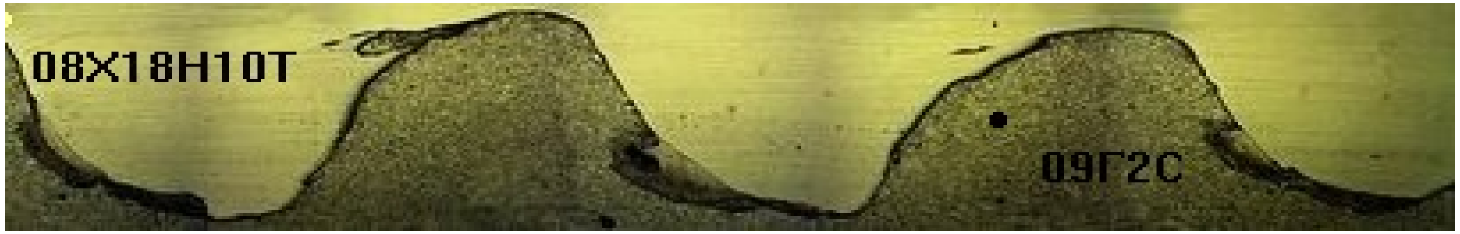




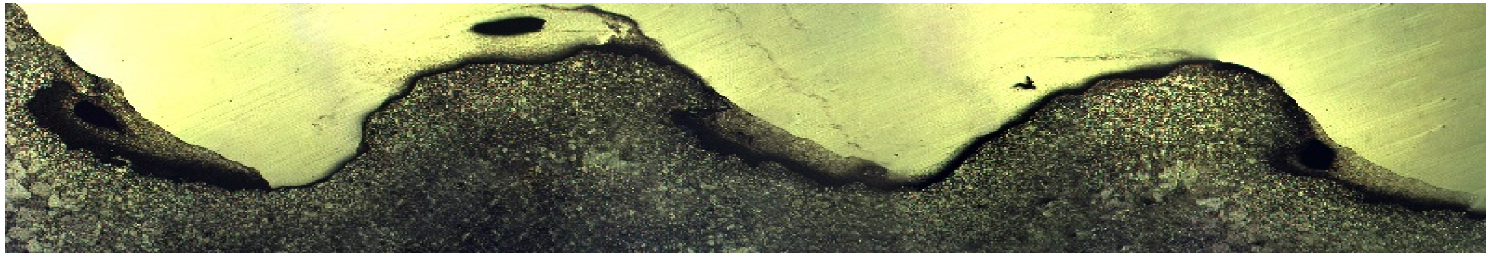
Cutting scheme



Typical structures at different distances from the process beginning



1000 mm

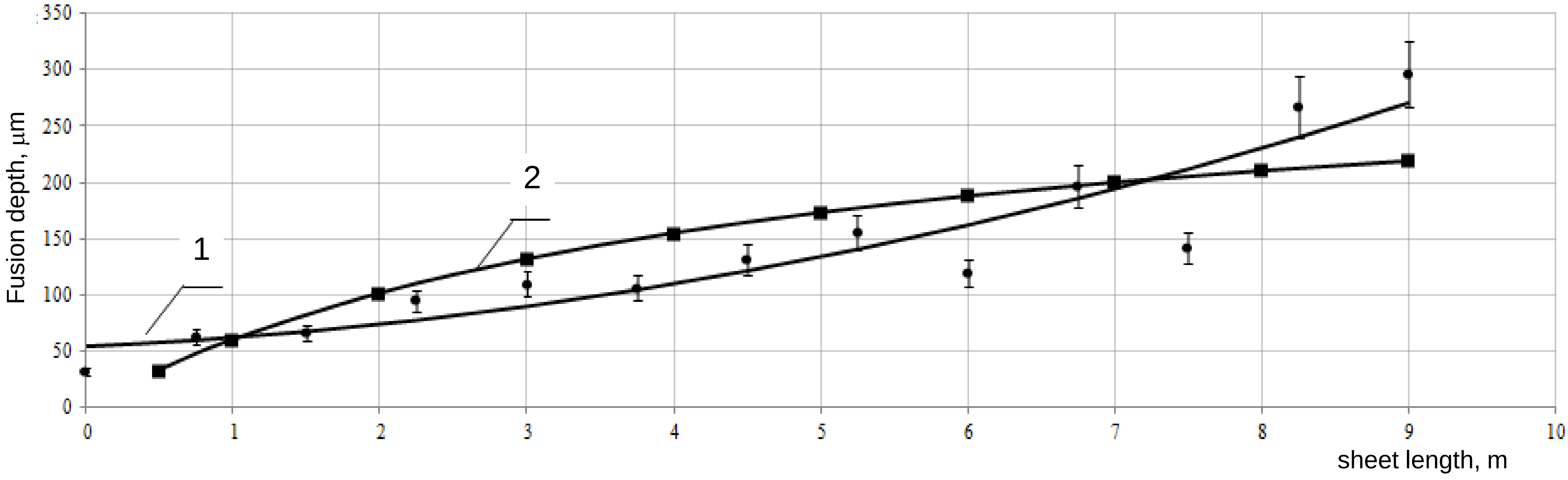


6000 mm.;

9000 mm

(X 100)

- According to theoretical calculations, shock-compressed gas can heat metal surfaces not more than 600° C at modes of explosion welding of large-size sheets. Impact of aerodynamic heating raises shock-compressed gas temperature in the interface (boundary layer) up to meanings sufficient for surfaces melting.

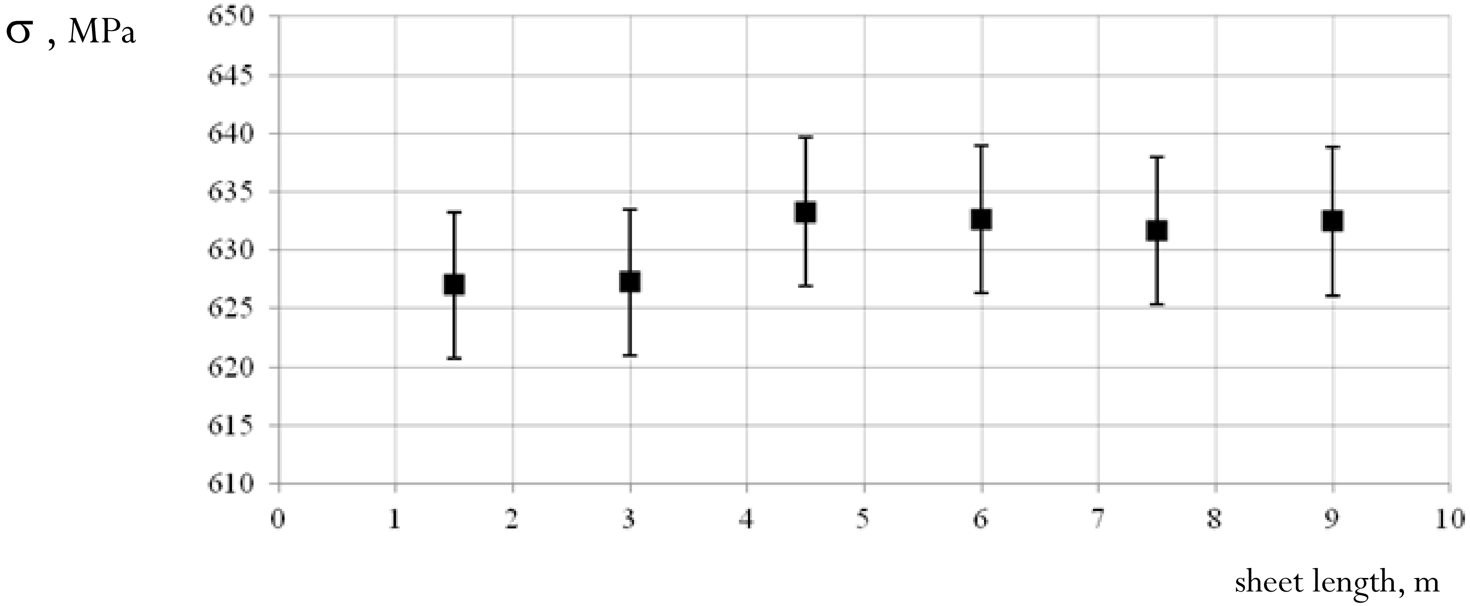


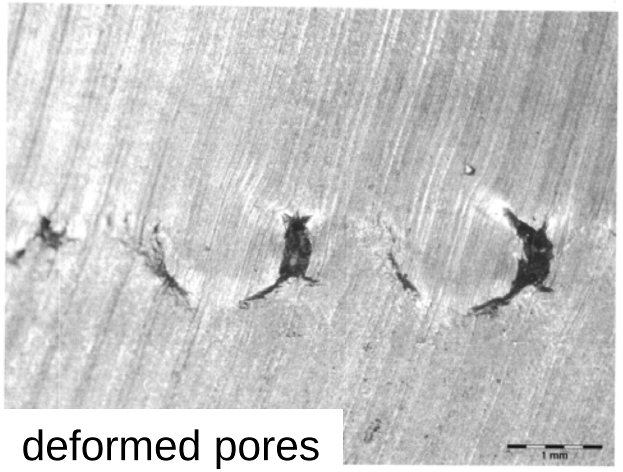
(1) experiment and (2) calculation.

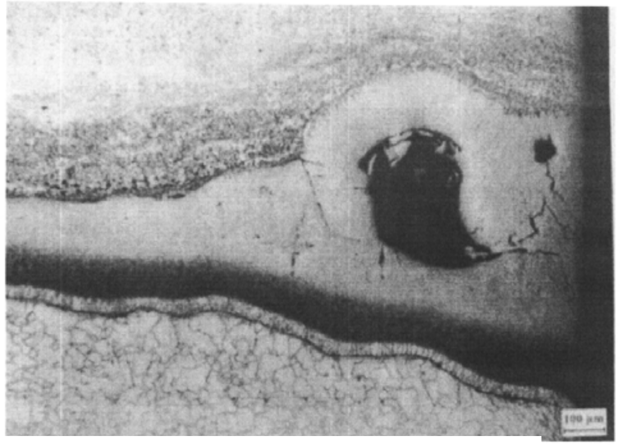
Mechanical tests

Bending tests (9 m)

Tensile strength testing

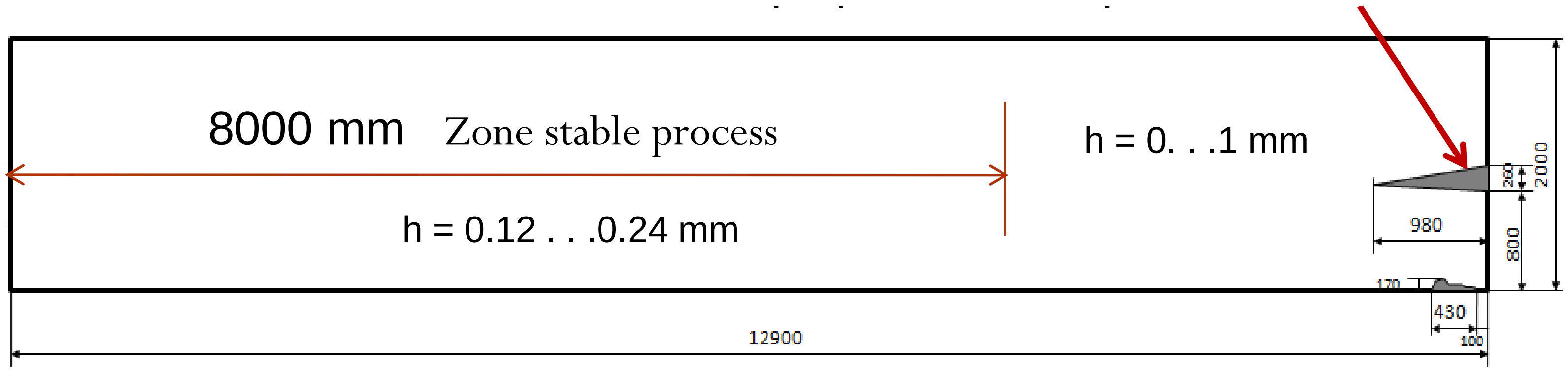



deformed pores


micro-cracks development
in the cast layer

Investigation of microstructure defects

Template



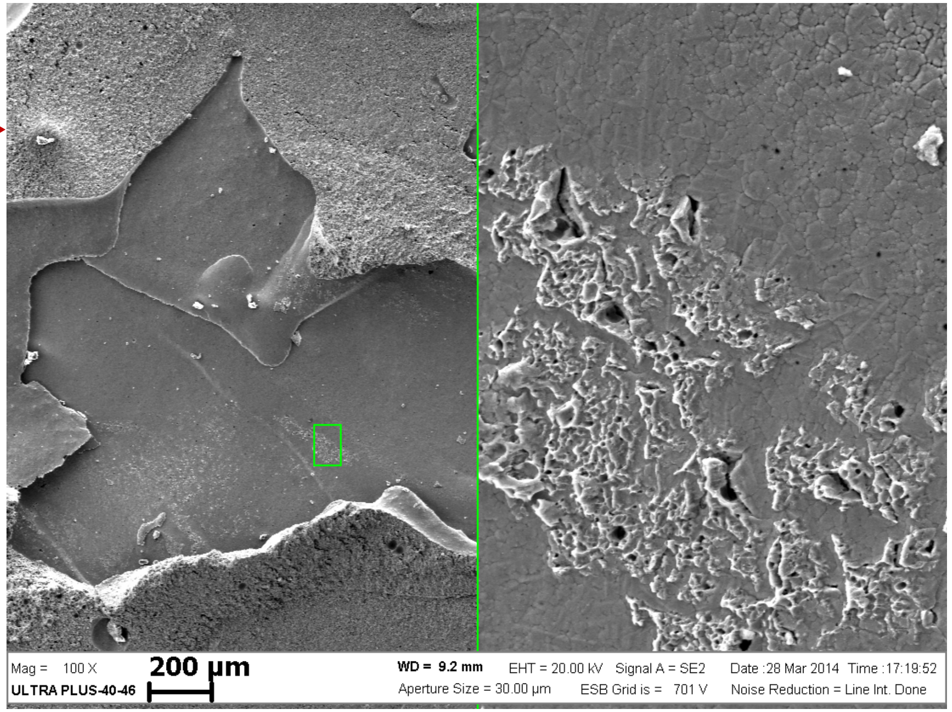
8000 mm Zone stable process

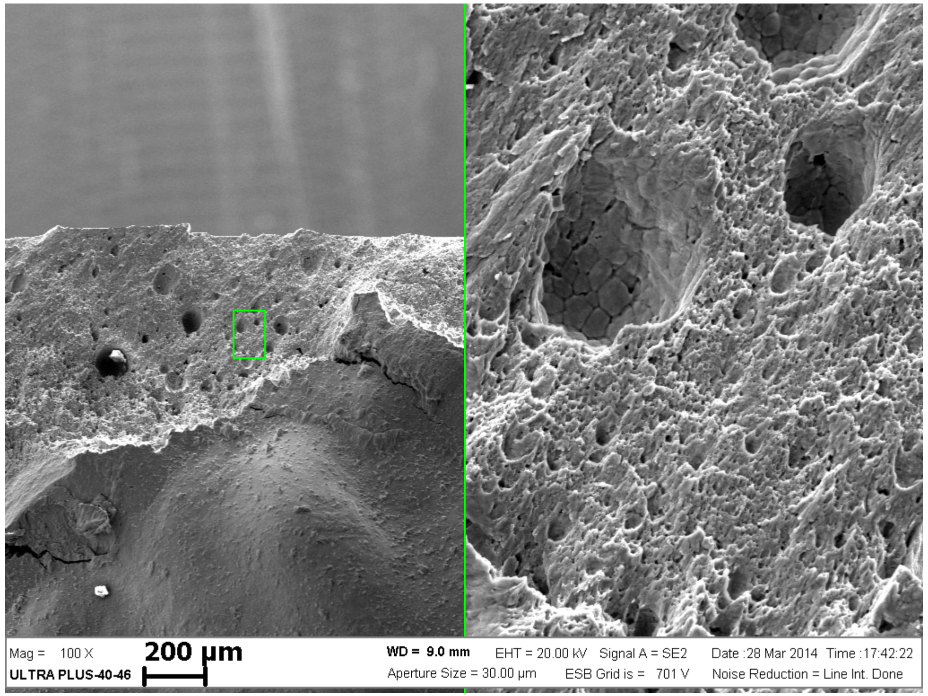
h = 0.12 . . .0.24 mm

h = 0. . .1 mm

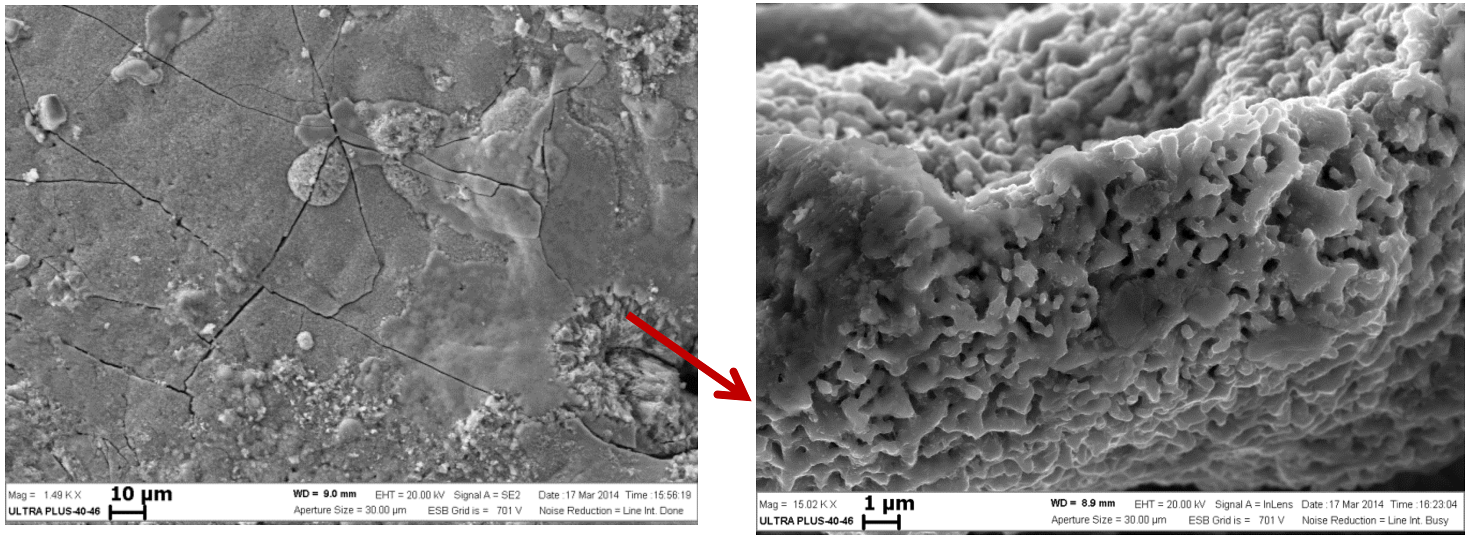
upper layer is bright and ductile

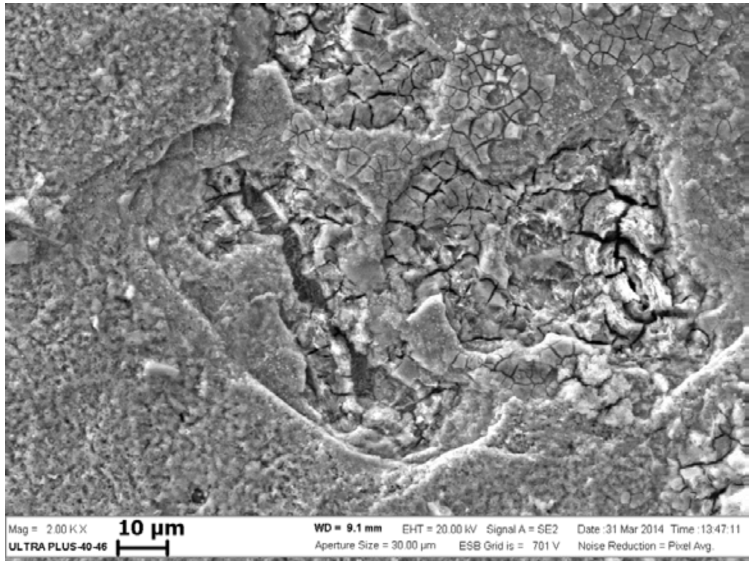
lower layer is dark and fragile

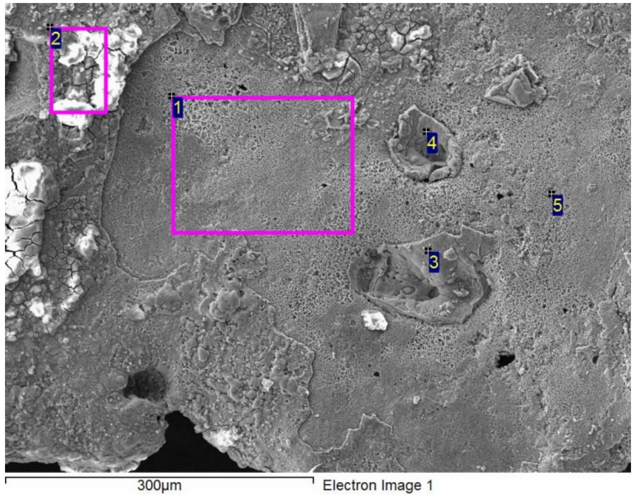




Structure and chemical composition of brittle layer

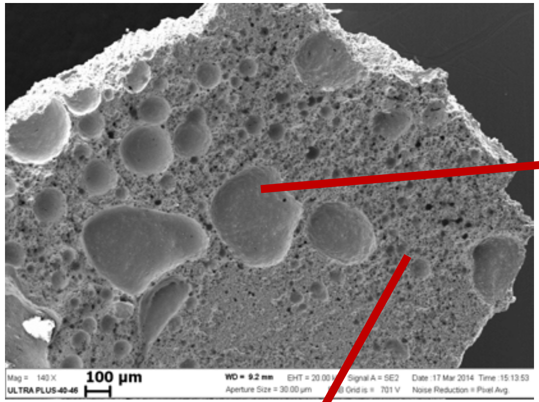


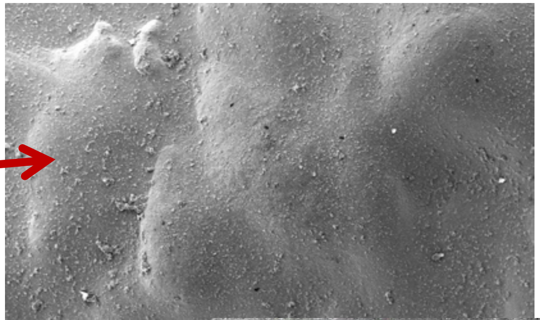


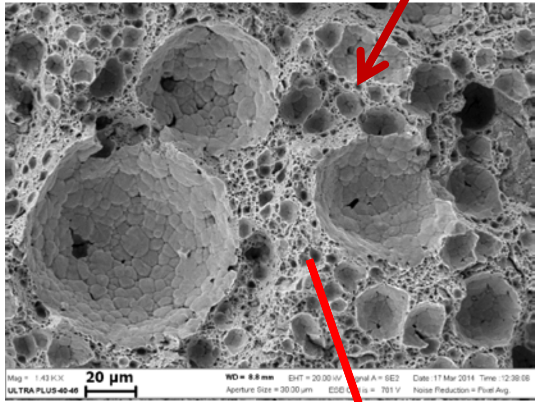


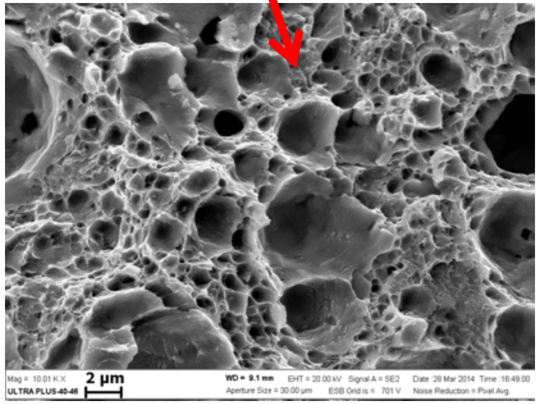
	C	O	Na	Al	Si	Cl	Ti	Cr	Mn	Fe	Ni
1	5.31	**22.60**		1.06	1.05		0.44	7.06	1.05	**52.41**	9.01
2	6.01	**37.08**	2.00	0.86	2.31			3.44		**47.25**	1.04
3	3.42	**41.64**	1.45	1.41		1.30		1.02	1.21	**48.54**	
4	2.13	**43.10**		1.19				0.71		**52.86**	

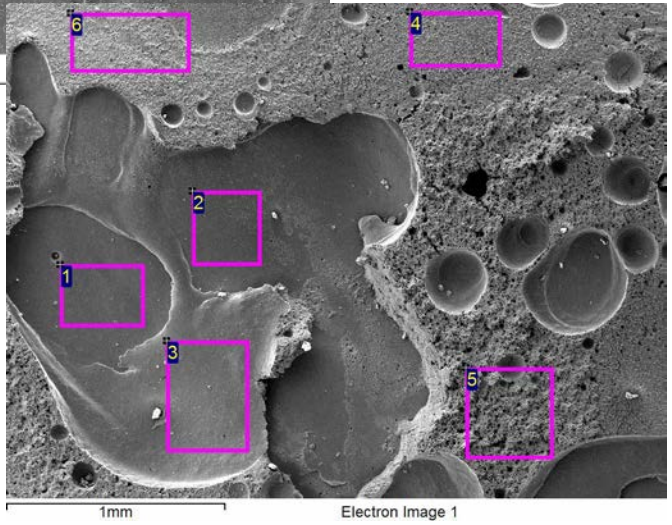
ductile layer



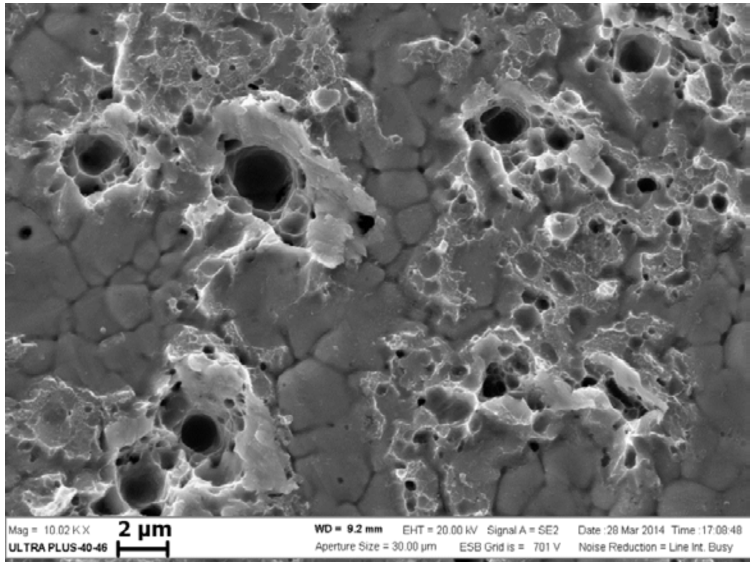


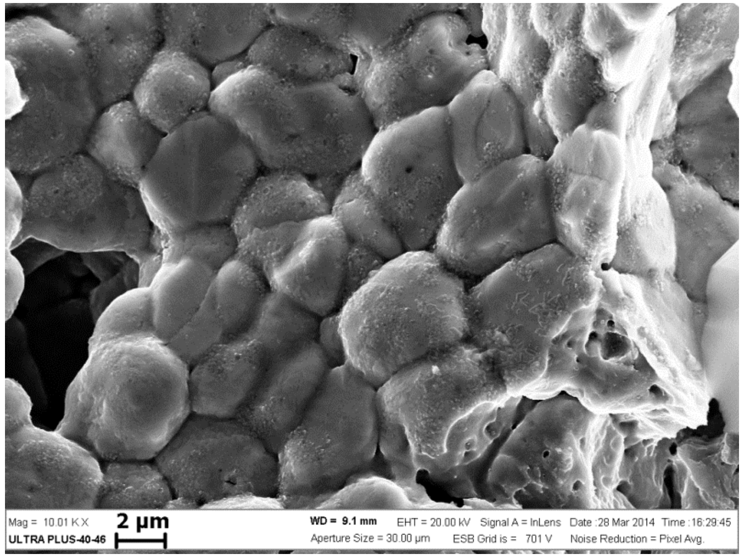




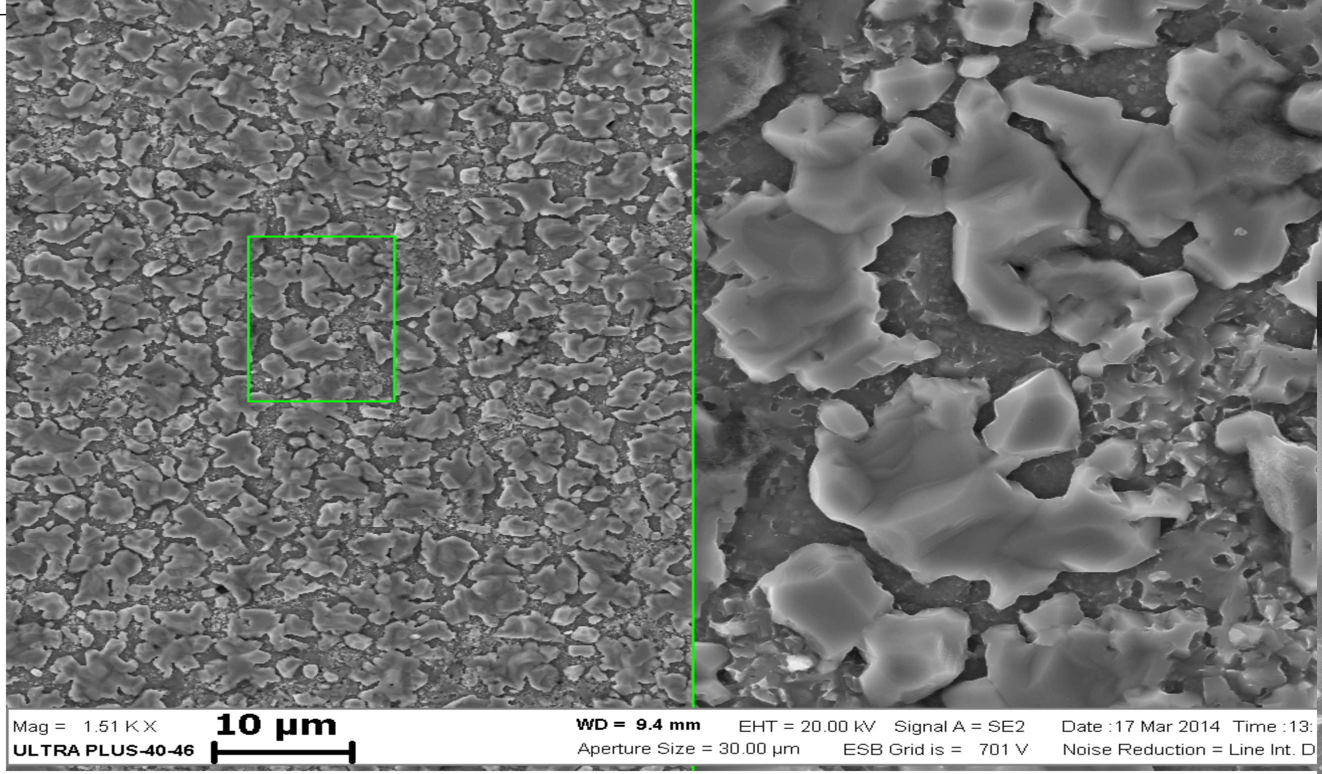


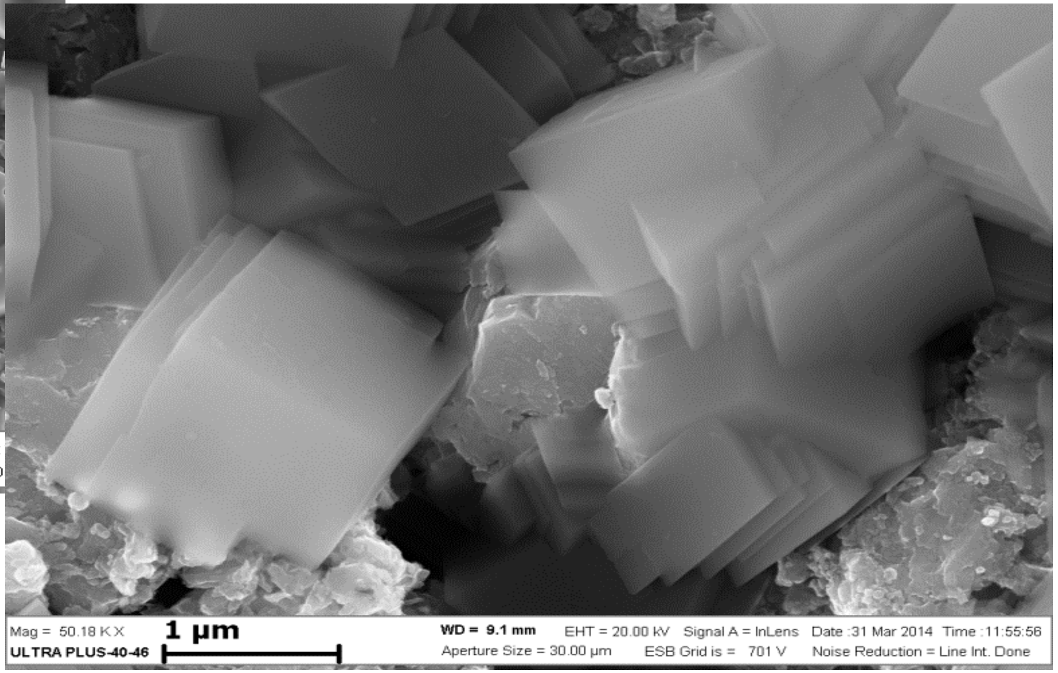
	O	Al	Si	Cr	Mn	Fe	Ni
1	2.40	1.06	0.56	10.29	1.52	79.43	4.73
2	2.24	0.76	0.56	9.98	1.69	79.67	5.10
3	1.83	1.16	0.71	10.60	1.34	78.95	5.40
4	2.57	0.68	0.80	10.41	1.74	79.53	4.26
5	1.42	1.26	0.52	10.81	1.70	79.93	4.37
6	1.40	1.02	0.37	10.46	1.21	80.69	4.86

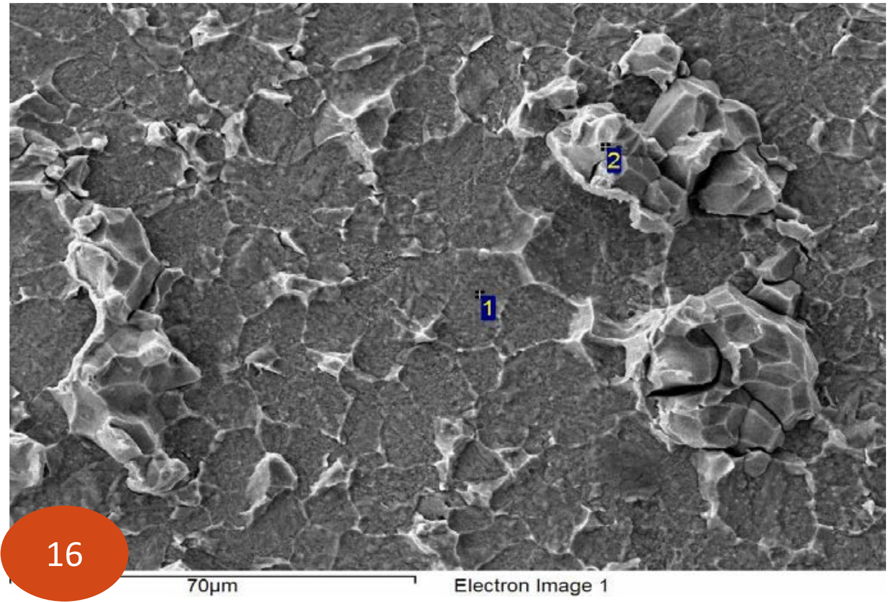




ductile layer

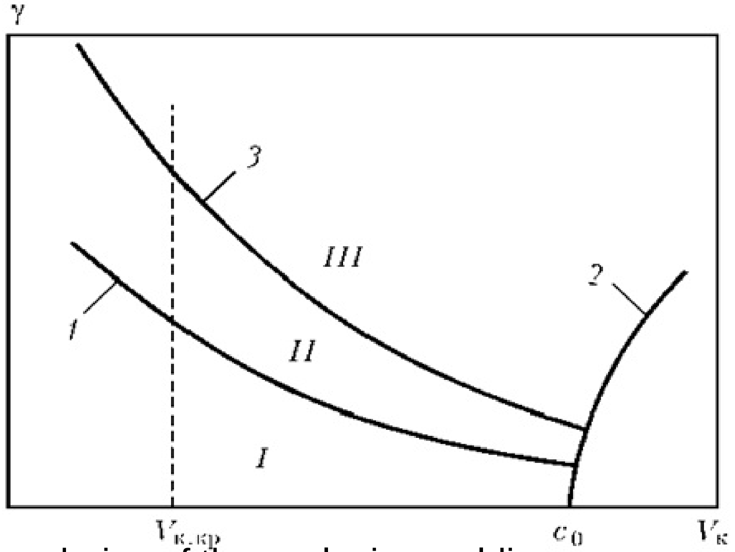




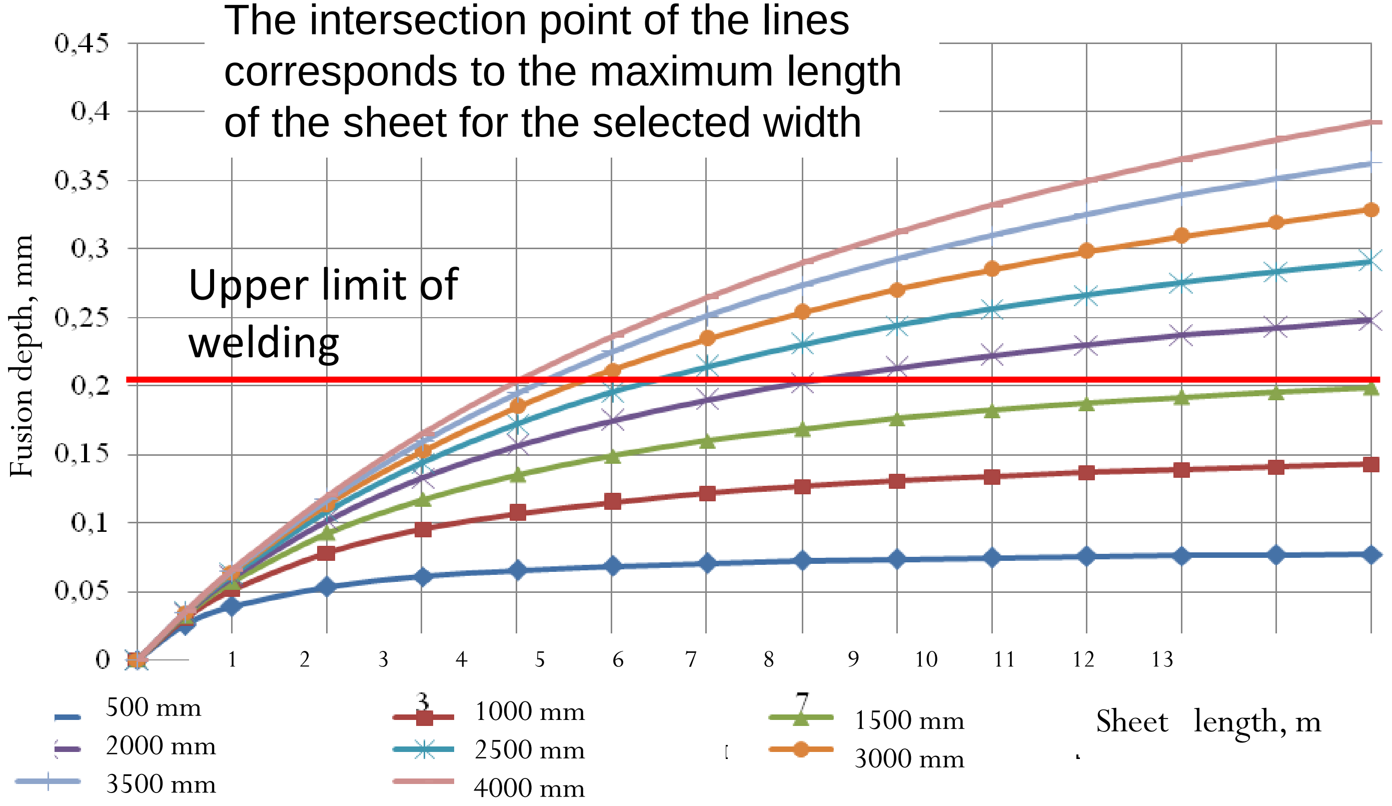


	O	Al	Si	Cr	Mn	Fe	Ni	Total
1	0.61	0.59	0.42	7.17	1.23	**86.78**	3.20	100.00
2	1.30	1.81	1.11	0.84	1.73	**92.97**	0.24	100.00

1. Calculations and experiments have shown that the surface to be welded is heated to high temperatures before impact and melting occurs. The fusion depth is proportional to the exposure time of the shock-compressed gas. The emergence of the molten layer on the surfaces prevents compounds formation in solid phase. This is accompanied by sharp change in the waves size and appearance of cast inclusions.
2. Determined the upper limit of high-quality welding of large-size carbon steel/stainless steel sheets which corresponds to fusion depth not more than 0.2 mm.



The boundaries of the explosion welding
1, 3 - the lower and upper bound, 2- supersonic boundary.
I - area subcritical mode (no welding), II - the region of explosion welding, III - the area exorbitant modes



The intersection point of the lines corresponds to the maximum length of the sheet for the selected width

Upper limit of welding

Conclusion

•Distribution of waves and inclusions over the length of large-sized sheet indicates that surfaces melt ahead of the contact point during explosion welding due to aerodynamic heating (convective heating and radiation). As a result of hypersonic flow of shock-compressed gas (up to 3000 K), unsteady shock plasma is formed in the interface (boundary layer). Presence of crystals and pure iron formed as a result of iron oxides destruction confirms plasma impact.

•Распределение волн и включений по всей длине большого размера листа указывает на то, что поверхность металла расплавляется перед точкой контакта во время сварки взрывом из-за аэродинамического нагрева (включающего конвективный нагрев и радиационное излучение).
•В результате гиперзвукового потока ударно-сжатого газа (с температурой до 3000 К), в пограничном слое между ударно-сжатым газом и металлической поверхностью образуется нестационарная ударная плазма. На воздействие плазмы указывает наличие кристаллов и слоя чистого железа образовавшегося вследствие разложения окислов железа и последующей кристаллизации.