Combustion effects in laser-oxygen cutting: basic assumptions, numerical simulation and high speed visualization

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Abstract

Laser-oxygen cutting is very complicated for theoretical description technological process. Iron-oxygen combustion playing a leading role making it highly effective, able to cut thicker plates and, at the same time, producing special types of striations and other defects on the cut surface. In this paper results of numerical simulation based on elementary assumptions on iron-oxygen combustion are verified with high speed visualization of laser-oxygen cutting process. On a base of assumption that iron oxide lost its protective properties after melting simulation of striation formation due cycles of laser induced non self-sustained combustion is proposed. Assumption that reaction limiting factor is oxygen transport from the jet to cutting front allows to calculate reaction intensity by solving Navier - Stokes and diffusion system in gas phase. Influence of oxygen purity and pressure is studied theoretically. The results of numerical simulation are examined with high speed visualization of laser-oxygen cutting of 4-20 mm mild steel plates at cutting conditions close to industrial.

Keywords: cutting; oxygen; combustion; simulation; visualization

1. Introduction

Laser cutting of mild steel with oxygen is widespread industrial technology. It is effectively used to cut mild steel sheets up to 25 mm thick. Owing to an additional energy release from combustion, the velocity of oxygen laser cutting of mild steel sheets up to 25 mm thick is several times higher than that in an inert gas cutting Poprave et al.

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Laser oxygen cutting is extremely sensitive to the condition of the sheet surface, metal composition, and especially to purity of oxygen used. The use of specially prepared metal and high-purity oxygen makes the technology more expensive Poprave et al (2004). Though this technology is widely used, its physical basis has not been adequately studied, many phenomena observed in this process and affecting the cutting quality cannot be explained. At recent stage the development of the technology was done mostly in experimental way, without noticeable theoretical input.

Qualitative theoretical assumptions on the process were formed in Ivarson et al,(1991), (1994). Elementary approaches postulated in those works were unable to predict most of phenomenon’s observed in cutting and couldn’t be used for calculation of values describing influence of combustion on cutting process: reaction rates, striation formation, melt removal and so on. For a long time the only results of those studies was a number of “guidelines”. Powell et al (2009), theoretical study of laser oxygen cutting should fit to. The problem solution was complicated with absence of reliable experimental data for verification of theoretical and simulation results. Results of cutting experiments give only indirect information such as cutting speed and surface pattern permitting multiple choices of probable physical processes combinations taking place in a cut kerf.

High speed observation of cut kerf formation laser oxygen cutting was done with side positioned camera only for thin plates Miyamoto & Maruo (1991) and those results are not sufficient for demands of simulation and industrial customers. Other ways of experimental modelling haven’t been used because of low relevancy to studied process. It includes combustion of exact material, gas dynamics with absorption on a combustion surface, radiation propagation, melt flow and heat transfer problems to be modelled simultaneously.

In this work we present together several complexes consisting of basic physical assumptions on a process, prolonged with mathematical formulation of the problem and results of its numerical simulation compared with high speed observation of laser oxygen cutting process of mild steel plates up to 20 mm thick.

2. Striation formation at the upper part of the kerf

In our earlier publications Ermolaev et al (2006), (2009), we demonstrated the following condition of striation formation due to cyclic combustion: the linear velocity of the combustion front should be higher than the cutting velocity. If this condition is satisfied, the combustion front initiated by the laser beam moves faster and leaves it behind, reaches the non-heated metal, and distinguishes; as a result, a certain combustion type of striations is formed. If the cutting velocity exceeds the linear velocity of combustion, then the reaction front fails to leave the laser beam and the process proceeds in a steady mode. The main guiding assumptions of presented simulation are:

- Mild steel ignition point is equal to melting point of iron oxide, 1640 K
- Oxide layer is thin, intensive reaction takes place in local area where oxide layer is fully melted
- Reaction intensity is limited with oxygen transport from the oxygen jet to combustion front
- Main heat losses from the cutting front takes place due to the heat conduction to the material of the work piece

Those assumptions allow simulation of striation formation by solving heat conduction equation with moving boundaries and temperature dependent heat source, Ermolaev et al (2006), (2009). As the result 3D dynamics of cut kerf surface formation is presented in Figure 1. Distance from symmetry plane to the cut kerf surface is marked with colours. Such a wavy profile is formed as the cutting velocity is low, in this case it was 20 mm/s. Periodically repeated ignition, combustion and extinguishing cycle begins at the time moment when the beam moving along the OX axis with the constant velocity moves onto the leading edge of the cut, Figure 1, a. Reaction initiation occurs at the moment when the laser-beam center is at the distance of 80 – 85 μm (1.25 σ) behind the solidified leading edge. At this moment, only the periphery part of the beam interacts with the sheet surface. The central part of the beam which contains the major part of the energy, acts on the material in the cut depth. The combustion wave initiated on the top edge begins to propagate in the metal extensively, the propagation of the top zone of combustion is radial as it seen on Figure 1, b.
Since the problem has the preferential direction - vertical axis OZ, the combustion wave moves initially ahead of the beam in the plane of the top sheet surface and at some moment reaches the unheated metal region; the radial motion of the combustion wave decelerates and even completely stops, Figure 1, c. The part of the combustion front directed toward the sheet depth is still moving parallel to the cut front where the metal is well heated by the radiation, at the same time the reaction distinguishes on the upper surface of the plate, Figure 5, d. Simultaneous existence of two combustion waves is possible. Figure 1, e shows that the first wave has not yet propagated over the whole cut depth when the beam has moved and initiated a new combustion wave on the surface. The cyclicity of the process provides the regular formation of striations, Figure 1, f.

The same process was observed at low speed cutting of 4 mm mild steel with fiber laser Figure 2, Yudin et. al. (2010). Repetitive cycle of the cutting front formation is observed. Moving luminescent area intermittently appears in the upper part of the kerf, it is identified as a combustion waves. Its borders are visible due to the dynamics of the kerfs sideview and luminescence of the material. Figure 2, frame 1, evolved combustion wave is moving downwards. It’s upper and reverse boundaries are marked with redline line. Forward point of the combustion wave is marked with blue circle. Movement and intensive luminescence are not observed near upper surface of plate at this time moment. Figure 2, frame 2, new combustion wave is ignited on the top surface of the plate. Propagation on the top surface and near it takes place, frames 2-4. In simulation propagation of combustion wave at this stage was close to radial. The speed of propagation can be measured regarding from the front point movement and is about 30-40 mm/s in this experiment, and we can assume it to be radial too. The filming is performed in the reference system of the laser beam, thus cutting front displacement to the right signifies its speed is higher than the speed of material feeding. Figure 2, frame 4, combustion wave reaction distinguishes on the upper surface of the plate and begins to move downward, Figure 2, frame 5-6. Process tracking of wave vertical movement may be done referring to extinction front, which is distinctly visible on the frames. Its speed, measured basing on the slope of the line, is 7 mm/s. Representative frequency ignition cycles is about 100 Hz. Thus, at the cutting speed of 20 mm/s, the striations are approximately 0.2 mm wide. An interesting result is a fact, that generated oxide metal melt flow is being collapsed by surface tension forces and removed downwards by the assist gas in the form of thin jet, the dispergation of the molten material is observed inside cut kerf.

Such a cyclic tendency in glowing regions dynamics was observed by Miyamoto & Maruo (1991) at the high speed filming of the top surface of the sheet during the oxygen laser cutting of low-carbon steel.
Generally observed phenomenon show the same trends with results of simulation of combustion cycles striations formation Ermolaev and Kovalev (2009) based on the following general assumptions ignition temperature is equal to oxide melting point, liquid oxide layer is thin and chemical reaction rate is limited by oxygen transport from the jet to oxide surface. In simulation and in observation two stages of combustion wave propagation radial and vertical are observed, obtained velocities of combustion wave propagation a very close to measured ones.

In contrast to the calculations, new wave initiation in some experiments occurred not only on the cutting front, but at times also on the lateral surface in case the previous wave has moved the cutting front forward for a sufficient distance. As a rule, the wave ignited far from the cutting front, decays shortly, i.e. this is the case of afterburning of a small area, remained after more intensive wave propagation. No thick oxide layer accumulations or droplets are observed on a cut front, the thickness of liquid layer seems to be much smaller than kerf width or striation size. The modelling assumptions are suitable only for several upper millimeters of cut front, where the amount of liquid is not sufficient to change heat transfer in vertical direction, and cutting front propagation is limited with heat conduction process in solid metal.

3. Calculation of reaction intensity.

The calculation of chemical reaction intensity is cornerstone problem for understanding of oxygen laser cutting. Numerous experimental investigations studied the effects of oxygen pressure and the amount and composition of impurities in oxygen on the oxyfuel and laser cutting processes Wells (1955), Chen. (1998), Chen et al.(1999), Poncon et al. (1998), Miyamoto & Maruo (1991), Powell (2009). It clearly shows that reaction limiting factor is oxygen transport from the jet to cutting front. The anomalously high sensitivity of the cutting velocity to oxygen purity is usually explained by the effect of the Stefan flow Wells (1955), Chen. (1998), Chen et al.(1999). Even a small amount of the inert impurity restricts the access of oxygen to the cut front. The reaction intensity on the cut front was not calculated, and the impurity concentration and the oxygen jet flow in the cut kerf were not studied. The range of oxygen purity with a small amount of the inert impurity was not adequately studied either; as a consequence, the sufficient level of oxygen purity exerting a favorable effect on laser cutting was not determined. At the same time in high speed filming, Figure. 2, thick oxide accumulations that can limit the reaction rate are not

![Fig. 2. Cyclic combustion at laser cutting of 4 mm thick mild steel with 2kW fiber laser. Cutting speed 20 mm/sec, oxygen pressure 1.5 bar, nozzle diameter 2 mm, standoff 1 mm. Interval between the frames 2 ms.](image)
observed. We can propose that liquid oxide layer is thin and doesn’t limit oxygen transfer from free surface to metal boundary. The main guiding assumption are, Ermolaev and Zaitsev (2012):

- Reaction intensity is limited with oxygen transport from the oxygen jet to combustion front.
- Oxide layer is thin and doesn’t limit oxygen transport in a process.

The Stefan flow is formed in case of a high concentration of one reagent in diffusion-controlled heterogeneous reactions with a large change in the gas-phase volume. Physically, it exhibits in the formation of a laminar boundary sublayer filled by a neutral impurity and as the emergence of a normal-to-surface component of velocity in the flow core. Oxygen has to diffuse to the reaction surface through this thin laminar sublayer filled by a neutral impurity. The rate of oxygen consumption is so high that it makes the entire flow core turn toward the metal surface. The dependence of the reaction rate in the range of small amounts of the inert impurity is principally different from Fick’s law. In classic Stefan flow formulation several simplifying assumptions are used: a transition to a pseudo-one-dimensional problem is performed, the flow velocity is assumed to be essentially subsonic, and the inert impurity content is assumed to be appreciable (1% or more). Obviously, most of these conditions are invalid for oxygen laser cutting. The Stefan flow is an approximate solution of system (1)-(5):

\[
\frac{\partial \rho_{\text{O}_2}}{\partial t} + \text{div} (\rho_{\text{O}_2} \vec{V}) = \text{div} (D \nabla \rho_{\text{O}_2})
\]

\[
\frac{\partial \rho_{\text{N}_2}}{\partial t} + \text{div} (\rho_{\text{N}_2} \vec{V}) = \text{div} (D \nabla \rho_{\text{N}_2})
\]

\[
\rho = \rho_{\text{O}_2} + \rho_{\text{N}_2}; \quad p = \rho T; \quad E = c_v T + \frac{V^2}{2}
\]

\[
\rho \left( \frac{\partial \vec{V}}{\partial t} + (\nabla \vec{V}) \vec{V} \right) + \nabla p = \nabla \cdot \vec{S}
\]

\[
\frac{\partial}{\partial t} \rho E + \text{div} (\vec{V} (\rho E + p)) = \text{div} (\lambda \nabla T) + \text{div} (\vec{V} \cdot \vec{S})
\]

Equations (1) and (2) describe the diffusion of oxygen and the inert component of the mixture in the gas flow; in this study, we consider only one inert impurity (nitrogen).

Equations (4) and (5) form a system of Navier-Stokes equations and describe the gas flow as a whole. The boundary conditions for these equations on the metal surface everywhere except for the cut front are the no-slip condition and the impermeability of the walls for the gas. The conditions on the cut front are the pressure equal to the equilibrium pressure of the chemical reaction for oxygen and the no-slip condition for the impurity.

We solve system (1)-(5) numerically under the geometric conditions of laser cutting, Ermolaev and Zaitsev (2012), Figure 3.

The results of the simulation are presented on Figure 4. On the base of calculated results, we can identify several ranges of oxygen purity with different physical mechanisms limiting the reaction rate.

It is found that a sublayer filled by the inert gas is formed near the cut front if low-purity oxygen is used (below 99.5%). The reaction rate is determined by the rate of oxygen diffusion through this sublayer. This fact agrees with the widely used hypothesis and experimental cutting results for low purity oxygen Miyamoto & Maruo (1991), Powell (2009).

If the oxygen purity is greater than 99.5%, then the inert sublayer thickness is so small that the reaction rate is determined by the rate of gas supply to the cut front from the flow core, i.e., by gas-dynamic effects.

The oxygen concentration of more than 99.99% is insufficient for any considerable inert sublayer to form, and the reaction rate is determined exclusively by gas-dynamic effects inside the kerf; a further increase in the oxygen purity does not lead to any noticeable increase in the reaction rate; as a consequence, this oxygen purity value is excessively high for laser cutting.

Gas flow pattern inside cut kerf for high purity oxygen and reaction intensity distribution on front wall are presented on Figure 4. A, B. If extremely pure oxygen (99.99% and more) is used, the amount of the inert impurity contained in the jet is insufficient to form a sublayer capable of limiting the oxygen flow toward the surface. The
oxygen flow toward the cut front is limited exclusively by gas-dynamic mechanisms.

As in the previous case (99.5-99.9% purity of oxygen), there is a low pressure area at the initial part of the cut kerf, which overcomes the jet inertia and makes the jet turn to the surface. Further inward the cut kerf, however, the inert sublayer capable of freezing the flow turned to the surface is not formed. The velocity of the oxygen flow normal to the cut front behind the low pressure region, at a depth of 2-3 mm, is limited by the natural sonic barrier of 330-340 m/s. As is seen from Figure 4 B, the chemical reaction intensity in this case reaches 200 kg/m²s, the total rate of oxygen consumption is 200 mg/s, the characteristic size of the reaction intensity peak is up to 5-6 mm, and the intense reaction proceeds over the entire sheet thickness.

The rate of oxygen consumption in the cut front is shown in Figure 4C as a function of oxygen purity in the logarithmic scale. For the impurity content above 0.5%, the reaction rate is determined by diffusion through the inert sublayer, which agrees with Stefan’s flow. After that, the reaction rate is limited both by diffusion through the inert sublayer and by gas-dynamic effects. As is seen in Figure 4 A-B, oxygen consumption in the cut front drastically changes the gas flow pattern in the cut kerf, and additional specific features depending on oxygen purity appear. If the oxygen purity is more than 99.99%, the chemical reaction rate is determined exclusively by gas-dynamic forces.

Figure 4D shows the mass of consumed oxygen as a function of the pressure in the nozzle chamber for the oxygen purity of 99.9%. In the subsonic flow region, 0.1-0.89 bar, the oxygen consumption rate smoothly increases with increasing pressure. Transonic effects in the pressure range of 1-2 bar lead to three-fold reduction of the reaction rate; a further increase in pressure is accompanied by a smooth increase in the reaction rate. A certain decrease in the reaction rate at 5 bar is related to the displacement of the shock wave boundary and also the second peak of the reaction intensity from the cut kerf. Thus, the initial gas-dynamic conditions exert a significant effect on the reaction intensity and total rate of oxygen consumption in the cut front. It confirms that the reaction rate is determined both by oxygen purity and by gas-dynamic effects inside the cut kerf.

It should be noted that the use of high pressures does not lead to a proportional (or, at least, significant) increase in the reaction rate as compared with the maximum level reached at low pressures. There are only a certain changes in the shape of the reaction intensity curve over the cut kerf depth.

Those calculations shows heat release for model kerf 0.5 mm wide and oxygen of industrially used purity for about 3.5 kW, and power intensities on a material about 0.5-10⁹ W/m². For real thinner, 0.3-0.4 mm, cuts total chemical energy release might be in a range 2-2.5 kW, those meanings are quite close to laser power and intensity levels and can easily explain practically observed cutting speed increase in comparison with inert gas cutting. It is important to note that the length of intensive chemical reaction action is limited with 5-6 mm, and in our opinion can be hardly changed with nozzle geometry, oxygen pressure and plate thickness. The length of intensive reaction might be the one of process limiting factors of oxygen cutting.
The method of reaction rate and intensity calculation for oxygen laser cutting is proposed. The intensity of the iron-oxygen reaction inside the cut kerf is calculated as a function of oxygen purity and pressure by solving the system of Navier-Stokes equations with diffusion of the impurity in the gas phase.

Influence of oxygen purity and pressure on local reaction intensity and total reaction rate was studied numerically. It is shown that hypothesis of laminar sublayer formation is not valid in up to date industrial levels of oxygen purity and reaction limiting factors at high oxygen purities are compressible fluid dynamics effects taking place in a cut kerf.

High pressure flows are accomplished with number of subsonic and transonic effects that limit oxygen consumption on a cut front make reaction intensity distribution highly non-monotonic. A proportional increase in the reaction rate with increasing pressure is not observed. Subsonic flows are more preferable for thick section cutting due to higher reaction rates and smooth reaction intensity distributions.

The analysis of energetic contribution in a cut kerf shows power levels of 1.8-3 kW for 6mm plate and power intensities up to $0.5 \times 10^9$ W/m$^2$. Those values are close to laser power and intensities used in cutting, and explain high efficiency of oxygen laser cutting.

4. Cut kerf formation in thick section cutting.

General trends of cut kerf profile formation in oxygen laser cutting of thick plates are illustrated with high speed filming on Figure 5. Cut front in our opinion can be subdivided into three zones according to the nature of observed...
effects, Figure 5, frame 5. The boundaries between those zones are not strict because of non-stationary and stochastic nature of the process. Three zones on a cut front can be defined: the upper Zone I (0-1 mm), the middle Zone II (1-8 mm) and the bottom zone. Combustion waves regularly arise in the upper zone of the kerf, and form combustion cycles type of striations as we saw for thinner plates, Figure 1, Figure 2. Length of upper zone might be defined by two processes: heat conduction in solid metal with and action of low level step in reaction intensity at the entrance of cut kerf, Figure 4b. Further wave propagation down the cutting front in Zone II is less regular: some waves are attenuated; others amplified. In the bottom zone the process is stabilized, cutting front becomes smoother. It is reasonable to assume that striation formation due to combustion process takes place in area where oxygen from gas jet is available for the reaction. The depth of the middle Zone II (1-8 mm) of striation formation by intensive combustion is close to the depth of the of intensive oxygen transport from the jet to cutting front, Figure 4B. 

In the upper part there are regular small striations, which merge into large scale and more chaotic ones down the kerf 8-20 mm. The area covered with liquid material is shown on frame 1 with red dashed line. At the zone about 6-8 mm near the bottom of the kerf melt flow becomes very wide and shallow. At the beginning of the recording the width of the melt flow is about 3 mm, frame 1, and at the end of the observation, after about 0.08 s, it becomes 1.5 mm, frame 5. This long period melt flow oscillation produce large scale striation on a cut wall.

Melt flow in this area can be subdivided in to two parts, boundary is marked with yellow line, frame 1. Side area on kerf wall is low luminescent, that might indicate surface temperature much less than on cutting front. At the same time the thickness of liquid layer seems to be small. The second central part of the flow is situated near the cut front and is highly luminescent. We can suppose that temperature of the melt there is much higher than in the side flow. The border line between this to parts of the melt flow is always clearly seen. Melt ejection from the cut kerf takes place only from the forward highly luminescent area. The nature of long period melt flow fluctuations in this zone is unknown and in our opinion they are limiting factor in cutting of thick sheet with good quality.

High speed visualization of cut kerf formation in thick section cutting is done. General tendencies of cut front dynamics are analysed, three zones on a cut front are subdivided according to the nature of observed effects. Results of the observations might be partly explained with the results of numerical simulation.
5. Metallurgical interaction of oxide and mild steel.

As one can see cutting with oxygen is really complex process, some of the phenomenon can already be described, but still there is great number of influence factors that couldn’t be neglected in further studies of the process. One of them is metallurgical carbon-oxide-metal interaction. Some of the phenomenon taking place in cutting process are presented on Figure 6. Figure 6 A-D show interaction of oxide and steel with carbon in cutting process conditions. On Figure 6 A,B carbon particles frozen in oxide layer are presented.

Well known for oxyfuel cutting effect, Horn (1974), of main metal carbonization and formation of “white” martensite layer showed on metallurgical micro photos of kerf wall cross-section on Figure 6 D,C. “White” martensite layer might be 10-50 μm thick, and depends mostly on plate thickness.
Dissolution of solid steel with liquid oxide was fixed in heavy dross attachments in thick section cutting and presented on Figure 6 E,F. Rough boundary of iron-oxide interaction, Figure 6 E,F, and fallen out metal grains of non-spherical form, Figure 6 E, shows that liquid oxide (melting point 1640K) can intensively dissolve solid iron (melting point 1810K). This process can results in further destruction of the metal near cut front and in additional intensification of mass and heat processes in iron and oxide melt.

It is clearly seen that iron-oxygen-carbon interaction in cutting process is much more complex than wustite formation, as it is usually assumed to be. Shown on Figure 6 phenomenon are studied not satisfactory and might be key points for further development of the technology.

6. Conclusions

Iron – oxygen combustion is a fundamental process for oxygen laser cutting, at the same time it is highly complicated and consists of several subprocess: heat conduction problem, gas and melt fluid dynamic problem, chemical and metallurgical interaction of iron and other steel components with oxygen and many others.

Basic physical assumptions on iron-oxygen combustion are formulated. On their base several problems are formulated separately from the general complex of physical processes and solved numerically. Striation formation due to combustion cycles is obtained and shows the same trend with visualized striation formation of thin plate cutting. Intensity and heat effect of chemical reaction is calculated in conditions of cutting process. Influence of oxygen purity and pressure is studied theoretically. Calculated energy release and power intensities of the reaction are comparable with laser power and intensity levels and can easily explain practically observed cutting speed increase in comparison with inert gas cutting.

Results of the simulations are compared with high speed visualization obtained with a help of modified trim cut technique. Striation formation in simulation and visualization show the same trends. Predicted length of intensive reaction is well seen in changes of melt flow and striation formation for thick plates cutting.

Actual problems of thick section cutting and simulation – melt flow in bottom part of the kerf and metallurgical interaction of iron oxide with metal are marked to be obligatory steps in further studies and development of the technology

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References

Wells A.A. 1955. The iron oxygen combustion process. British Welding Journal, September, 392-400.
Horn V. 1974. Schweisstechnischer Gefügeatlas. VEB Verlag Technik, 361p.
Miyamoto I., & Maruo, H. 1991. Mechanism of laser cutting. Welding in the World, 29(9), 283-94.
Ivarson, A., Powell, J., & Magnusson, C. 1991. The role of oxidation in laser cutting stainless and mild steel. Journal of laser applications, 3(3), 41-45.
Ivarson, A., Powell, J., Kamalu, J. & Magnusson, C. 1994. Oxidation dynamics of laser cutting of mild steel and the generation of striations on the cut edge. Journal of Materials Processing Technology. 40, 3-4, p. 359-374 16 p.
Chen S. L. 1998. The effect of gas composition on CO2 laser cutting of mild steel. Journal of Material Processing Technology. Vol. 73, 147-159.
Poncon V., C. Guillais and C. Le Gall. 1998. Oxygen Quality in Laser Cutting for Low Carbon Steel and Stainless Steel,“ Welding in the World, V. 30 N. 9/10, pp 279-282.
Chen, K., Lawrence Yao, Y., & Modi, V. 1999. Numerical simulation of oxidation effects in the laser cutting process. The International Journal of Advanced Manufacturing Technology, 15(11), 835-842.
Poprave, R., Weber, H., & Herziger, G. 2004. Laser-Physics and Applications. Subvolume C: Laser Applications.
Ermolaev, G. V., Kovalev, O. B., Orlishch, A. M., & Fomin, V. M. 2006. Mathematical modelling of striation formation in oxygen laser cutting of mild steel. Journal of Physics D: Applied Physics, 39(19), 4236.
Ermolaev, G. V., & Kovalev, O. B. 2009. Simulation of surface profile formation in oxygen laser cutting of mild steel due to combustion cycles. Journal of Physics D: Applied Physics, 42(18), 185506.
Powell J, D Petring, R V Kumar, S O Al-Mashikhi, A F H Kaplan and K T Voisey 2009 Laser – oxygen cutting of mild steel: the thermodynamics of the oxidation reaction J. Phys. D: Appl. Phys. 42 015504
Yudin P, Ermolaev G, Verna E, Jouanneau T. Visualisation and Modelling of Combustion Effects at Laser Cutting of Mild Steel with Oxygen. // proc. 4th Pacific International Conference on Applications of Lasers and Optics PICALO 2010, March 23-25, 2010. Wuhan, PRC, paper 905 Ermolaev G.V., A.V. Zaitsev. 2012 Mass and momentum transfer of oxygen jet to the melt in laser cutting of mild steel / 31-th International Congress on Applications of Lasers & Electro-optics. Proceedings: Anaheim, CA, USA. paper 805, pp 309-312 1.