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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.

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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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(2004).

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.