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Modeling of flow separation of assist gas as applied to laser cutting of thick sheet metal

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The present paper describes the results of mathematical modeling of supersonic flows of a viscous compressible gas, obtained by numerically solving three-dimensional full Navier–Stokes equations, and also the results of experiments with visualization of gas jet flows in channels geometrically similar to the laser cut. Separation of the gas flow from the cut front is predicted numerically and then validated by experiments on a model setup. The gas flow structure arising in a narrow channel behind a sonic (conical) or supersonic nozzle is described. Specific features of originating in the flow separation on a smooth surface in a narrow channel are examined, and mechanisms controlling the separation are proposed. Flow separation directly affects the changes in the shape and structure of striations and is the one of main reason for the worse quality of the laser cut surface. It is shown that the changes in the structures of striations over the thickness of the sheet being cut are closely related to aerodynamic features of jet flows of the assisting gas in the cut channel.

1. Introduction

During laser tailoring or cutting, the metal within the spot of focused radiation melts and is removed by the jet of the assisting gas through the cut being formed [1–3]. One important parameter characterizing the cut quality is the size of roughness elements formed on the side surface under the action of the gas and radiation. For a metal sample with a fixed sheet thickness, high quality is ensured by an appropriate choice of radiation and gas flow parameters. The assisting gas in this case may be an inert gas (argon or helium), a neutral gas (nitrogen), or an active gas (oxygen) [1,2]. The jet of an inert or a neutral gas exerts only the force action on the liquid layer of the melt moving at the cut front, while the jet of an active gas (oxygen) imparts the energy of chemical reactions of oxidation in addition to the laser beam energy.

Despite the success achieved in using lasers for metal processing, the processes of melt removal from the cut have not been adequately studied. In particular, mechanisms of formation of roughness striations are poorly known. For thick materials with a large aspect ratio between the plate thickness and the cut width, the cut quality is much worse. One of the reasons is a reduction of shear and pressure force on the melt surface, acting from the gas on the melt and subsequent bad removal of the latter. There is also an urgent problem of the influence of the assisting gas on the quality of laser cutting of metals (in sheets up to 25 mm and greater). There are no reliable concepts of the mechanisms of processes inside the laser cut. It is impossible to record the processes under natural conditions [4] because the cut walls are not transparent and the processes involve high temperatures and reflected radiation. The research under natural conditions is confined to observations of particles leaving the cut channel and to inspecting the metal surface after it was affected by the laser. Despite a large number of publications on laser cutting, engineering achievements in this field are limited. These restrictions are related to

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Nomenclature

t time
$\{x, y, z\}$ or $\{x_\alpha, \alpha = 1, 2, 3\}$ Cartesian coordinates
p, ρ, T, μ, and χ pressure, density, temperature viscosity, and thermal conductivity of the gas
$\vec{V}$ and V velocity vector and absolute value of the velocity vector of the gas
u_α or u, v, w gas velocity in the x_α or x, y, z directions, respectively
u_0 characteristic velocity
ρ_0 and T_0 initial density and temperature of the gas
μ_0, and χ_0 viscosity and thermal conductivity of the gas at the initial temperature
Re and Pr Reynolds and Prandtl numbers
c_p, c_v, $\gamma = c_p/c_v$ specific heats at constant pressure and constant volume and the ratio of specific heats
R universal gas constant
E total energy
e internal energy of the gas
$S = \{S_{\alpha\beta}\} = \frac{\partial u_\alpha}{\partial x_\beta} + \frac{\partial u_\beta}{\partial x_\alpha}$ strain rate tensor
$\Omega, \partial\Omega$ area and its boundary
τ time step
h_x, h_y, h_z calculated grid pitches by the coordinates x, y, z, correspondingly

the problem of providing a high quality of laser processing and to the necessity of choosing an optimal ratio of a large number of physical parameters (velocity of the process, radiation characteristics, thermophysical properties of the material, thermodynamic parameters of the assisting gas, etc.) [5–7]. For all these reasons, physical and mathematical modeling of processes inherent in laser cutting of metals becomes extremely important.

Experimental selection of best performance for the technology of laser cutting is hardly possible due to the variety of physical phenomena, taking place inside the kerf during processing. There are no satisfactory mathematical descriptions of the phenomena, involved in laser cutting, available today. The reason is complexity of the problem, which is fundamentally three-dimensional. One should simultaneously solve many conjugated subproblems of continuum mechanics and optics to correctly describe the process, such as supersonic jet flow inside the slot; instable motion of the film of melt; heat transfer from the melt to solid walls with moving phase change interface; interaction of the material with the laser beam, which multiply reflects from cutting front and walls; generation of striated roughness and dross (resolidified material at rear surface), etc. According to [8], and opinion of other authors, direct computer simulation of the conjugated subproblems in full three-dimensional statement is still severely limited with capabilities of present-day computer techniques. It is well-known that assisting gas, being responsible for evacuation of melt from the cutting kerf, plays important role in the enumerated processes, particularly in case of thick material under cut. Emphasis is made on the influence of jet gas flow on the size of side-wall roughness.

The gas dynamics of laser cutting is the subject of research for many authors. Makashov et al. [9] discussed the possibility of an experimental study of specific features of gas dynamics in the course of laser cutting of metals. In particular, they proposed to study the gas flow in geometrically similar models with an increased scale. The distributions of the total and static pressures in the flow for conical nozzles in wide ranges of pressures of the assisting gas and geometric parameters of the models were measured. It was noted that the flow inside the cut channel had a complicated three-dimensional structure consisting of supersonic and subsonic regions separated by a system of shock waves. They were the first ones to mention the possibility of emergence of a reverse flow. Under real conditions, the presence of this reverse flow can result in accumulation of the melt and periodic breakdown of the upstream supersonic flow; in addition, atmospheric air may enter the cut and react with the melted metal.

With the use of shadowgraphy, Man et al. [10] examined the behavior of the assisting gas jet in a model laser cut with the walls made of transparent glass. To simulate the cut front, a steel plate 0.5 or 0.7 mm thick was inserted into the kerf. The influence of two types of nozzles (supersonic and conical ones) on gas dynamics inside the kerf was studied. Unfortunately, the shadowgraphs presented in this paper do not allow one to capture the specific features of the gas flow inside the kerf. In the experiments on laser cutting [10], it was found that a conical nozzle with an inert gas pressure of 10–30 bar produced a cut of the same purity and quality as a supersonic nozzle with lower pressures of 5–10 bar.

Attempts of calculation of gas dynamic flows inside the laser cut were performed, but they were restricted to one-dimensional or two-dimensional approximations. Duan et al. [11,12] used the analytical theory of plane supersonic flows of an ideal gas to describe gas dynamics of the jet in the case of metal cutting with the use of an inert gas. A pattern of propagation of expansion and shock waves was obtained; these waves are alternatively reflected from the cut front (boundary of the metal) and an artificially defined curvilinear boundary of the jet. They also presented photographs of stainless steel samples 5 mm thick with a good quality of the cut surface obtained by a supersonic nozzle. It was noted that gas flow separation in the laser cut is possible if the pressure gradient changes its sign from negative to positive.