

On the Vortex Formation Effect During the Application of a Nitrogen-Gas Assisted Laser-Fusion Cutting Technique to Stainless Steel

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Abstract: This paper focuses on the vortex formation effect during the application of a laser-fusion cutting technique. This industrial technique is typically associated with the ejection of a film of molten stainless steel blown off by a subsonic laminar jet of nitrogen gas used to assist the process. Without taking into account the transverse movement of the workpiece, we consider a 4 mm thick stainless steel plate. The resulting molten metal flow is assumed to be laminar, steady, viscous and incompressible. The numerical results reveal vortex structures adjacent to the walls at the entrance of the kerf, and a pair of eddies outside the kerf. Remarkably, these vortex structures can produce a separation point in the molten film, and thereby they can affect the surface quality of the processed material. The problem is investigated in the framework of a numerical technique available in the Fluent software, based on a volume of fluid (VOF) surface-tracking strategy and the enthalpy method to account for material solidification or melting.

Keywords: laser cutting, metal, inert gas, boundary layer, fusion, transfer, heat, vortex

1 Introduction

Laser-based cutting processes have wide applications in industry. It is obtained by focusing an intense laser beam on a workpiece, leading to its absorption on the kerf front. This process involves heat transfer and the kerf front surface is melted, while the produced melt film is blown off from the kerf by an assist-gas jet. The CO₂ laser is the most commonly used, especially for cutting thick sections, because of its better beam quality compared with the Nd: YAG laser of a similar power level [Gabzdyl et al. (1992), Chen (1998)]. Gas-laser cutting of metals has

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been studied theoretically and experimentally by many authors and developed in several papers. An analytical approximation of the heat conduction losses during the cut of metals was developed by Schulz *et al.* (1993), where it was deduced that a laminar boundary layer is required in order to keep a high cutting quality. Mas *et al.* (2003) allowed a better understanding of laser metal cutting by providing a consistent approach involving many physical phenomena occurring during the laser cutting process. Vicaneek *et al.* (1987) studied the ejection of melt from the laser cut kerf. They deduced that this melt is mainly driven by two forces exerted by the assist gas jet which includes: the frictional force at the gas/melt interface and the pressure gradient one. They also concluded that both contributions are of the same orders and their strengths increase both by augmenting the gas jet velocity and the kerf inclination angle. Abdulhadi (1997) proposed a purely experimental approach focused on the calculation of the affected zone, and the metallurgical transformations of steels submitted to the laser irradiation. Tani *et al.* (2003) proposed that the two mechanisms responsible for dross formation were the surface tension of the melt and the build-up of melt at the bottom resulting from an incomplete ejection of the molten material. O'Neill *et al.* (1995) analyzed the effect of oxygen purity on the quality of mild steel laser cutting. It was experimentally demonstrated that laser cutting with oxygen can ensure a high-quality surface of elements only if extremely pure oxygen is used; in the case of cutting thick sheets of mild steel, the operating pressures should be within 1.1–2.0 bar. The use of oxygen gas is not only producing a blowing off action on the melt, but also imparts additional energy due to chemical reactions. To cut stainless steels, aluminum, titanium and other high-alloyed steels, the inert-gas fusion cutting process is the preferred procedure. It is based on the use of high-intensity laser beams and intense inert-gas jet as nitrogen or argon. The gas acts simultaneously with the laser beam on the workpiece, by using a coaxial nozzle configuration. Knowing that stainless steels are important engineering materials, used extensively in several applications related to domestic items, industry, health, food processing, farming, aerospace, construction, . . . The stainless steel is difficult to cut by oxy-fuel methods because of the high melting point and low viscosity of the formed oxides [Hsu *et al.* and Yilbas *et al.* (1995)]. The simulation of gas flow inside the kerf performed by Kovalev *et al.* (2008), show vortices, where the largest vortex arised at the kerf outlet, where it was collected and accumulated the liquid flow down the channel walls. They also found that the shape of striations is directly affected. The study with the double nozzle concluded that the vortices disappear as the pressure in the external nozzle was increased. These vortices are the main responsible for the worst quality of the laser cut.

In another paper of Kovalev *et al.* (2009), it was obtained by solving numerically the three-dimensional full Navier–Stokes equations of a supersonic flow for a vis-

cous compressible gas, that the separation region displays a large-scale vortex flow with the liquid accumulated on the channel walls. Such motion of the assisting gas in real laser cutting enhances melt accumulation in the separation region, which directly affects the changes in the roughness shape and size.

The aim of the present paper is to investigate the vortex formation appearing inside and outside the kerf, and its effect on the surface quality of stainless steel sheet during nitrogen fusion laser cutting process. Fluent CFD software was used for the numerical solving of the problem.

2 Modelling

2.1 Hypotheses and extension domain

The process of inert gas laser cutting of steel can be divided into three steps, (i) the laser beam power is absorbed on the kerf front; (ii) heat transfer occurs, leading to the melting of the kerf front surface; (iii) the molten film produced is blown off from the kerf by the assist-gas jet. To deal only with the third part of the process, a thin canal is considered, supposing it as similar to the obtained pattern resulting from the laser cut.

In the present study, we will develop our own condition to close the system, since at the exit of the kerf, the boundary condition is not known. So, an extended region below the formed kerf is included in the computational domain and it must be enough large to avoid influence on the solution within the kerf, see figure 1. The velocity and the static pressure along the axial direction for the standoff region, the kerf, and the extension (axis1, axis2, axis3), are illustrated in figure 2. It is shown that a distance of '12mm' is enough so that the longitudinal gradients of velocity and pressure tend asymptotically towards zero at the exit of the extension.

In the present work, this extension is also necessary to take into account and to follow eventual eddies which may appear outside the kerf and then may affect the dynamical and thermal aspects of the molten film.

The molten film temperature is kept at the stainless steel melting temperature i.e 1712 K. This layer is supposed to be already formed at the initial time of the simulation, with a thickness of $50\mu\text{m}$. The gas jet temperature at the inlet kerf (1mm width) is 300 K and its velocity is fixed to 50 m/s.

The thin molten layer that remains on the cutting front is similar to a boundary layer [Schlichting (1982)], which flow can be specified by considering the following assumptions:

- The molten film is supposed to be laminar, viscous and its thickness is very small compared to the kerf size, which allows considering a 2D ejection.

- The slope of the cutting front is negligible.
- Since fusion laser cutting is considered, there is no vapour and plasma production.

Although for the gas flow, the following assumptions are made:

- The flow presents a boundary layer which is superposed to the molten layer located at the cutting front.
- The flow is laminar and subsonic with small Mach number ($M < 0.3$).

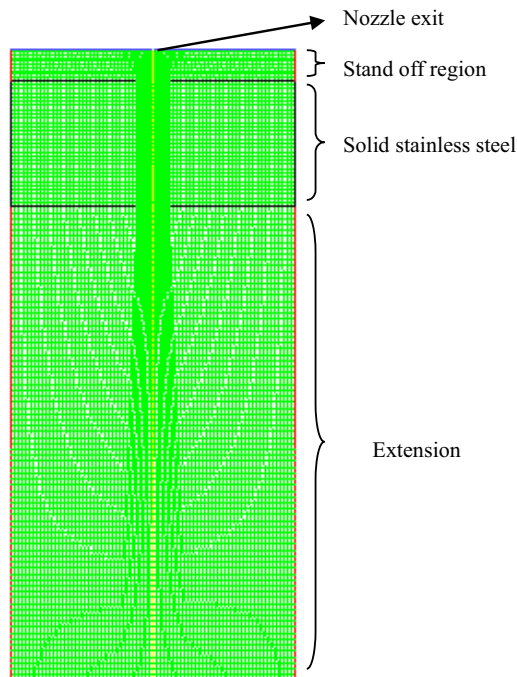


Figure 1: Mesh generated in the solution domain

2.2 Numerical method and simulation

The grid and the boundary conditions reservation were defined by the means of the pre-processor Gambit, whereas the computing was processed by Fluent to solve numerically the Navier-Stokes equations using finite-volumes method [Patankar (1980)].

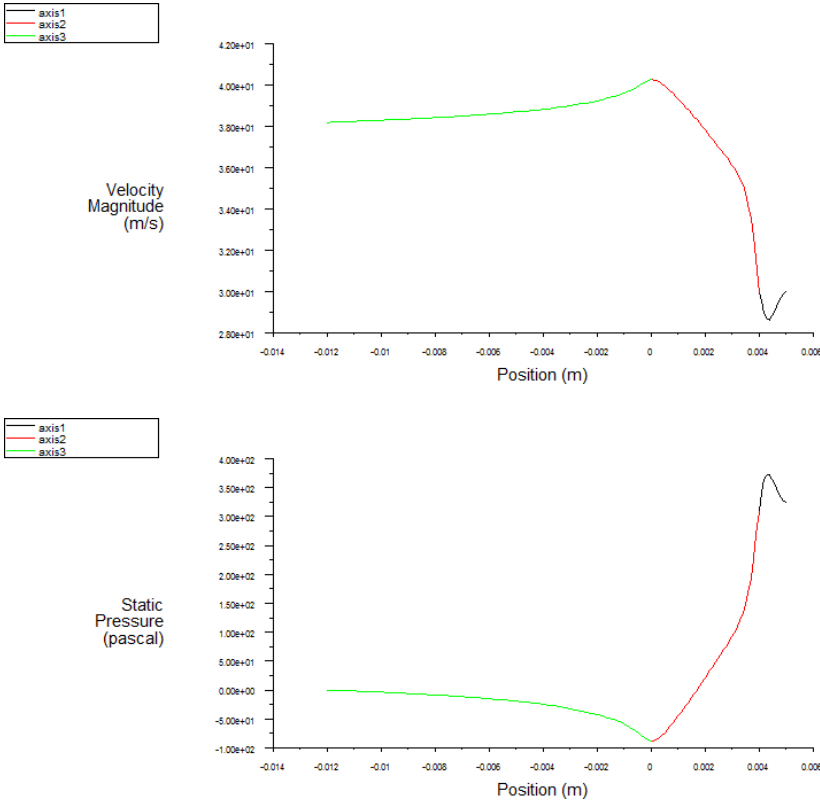


Figure 2: Axial velocity and pressure at $3 \cdot 10^{-4}$ s

This method consists to divide the domain into discrete volumetric elements and the physical quantities are defined in the centroid of each element. Over each element and using an interpolation function for the considered variable, the concerning conservation laws are integrated (velocity components and pressure). The obtained algebraic equations are then linearized and solved iteratively. The convergence of the iterative resolution is checked by the evolution of the individual values of every variable during iterations. The residual in each control volume is defined as:

$$R_\phi = a_P \phi_P - \sum_i a_i \phi_i - S$$

Fluent offers the possibility to simulate simultaneously incompressible and compressible fluids, as well as multiphase flow with free surfaces.

The so called volume of fluid (VOF) model is well appropriate for tracking sharp interfaces. In our case, the interface is between two immiscible fluids, namely

the molten stainless steel and the nitrogen gas. In our model, a volume fraction corresponding to the volumetric occupation of the regarding phase is introduced. So, Fluent provides the so-called geometric reconstruction scheme which is a discretization scheme for the volume fraction, where the interface between two phases is always ensured to be sharp. Several elements around the physical interface would be occupied by the both phases. Within the VOF model and the geometric reconstruction scheme the surface tension must be considered.

The change state of the stainless steel from liquid to solid during the cooling induced by the ejected gas is treated by melting and solidification model. This model is implemented in Fluent by an enthalpy based phase change approach; it includes a mushy region around the melting point, where the material is linearly changing from solid to liquid.

In this work the so-called pressure based segregated solver is used, because this is better for handling free surface flow. The momentum equation for the velocity components is solved sequentially by the algorithm; a pressure correction is calculated by solving a pressure equation to satisfy the continuity. This correction is used to update the pressure and velocity field. For this, the velocity components are stored at a location midway between the grid points, i.e. on the control volume faces. All other variables including pressure are calculated at the grid points.

During numerical resolution of the equations by the Fluent, user defined functions (UDFs) written in C++ programming language, extended by a library containing functions can be interactively loaded. In our case UDFs are used to define some physical properties of our material which depend on the temperature.

Our model is divided into two zones: a fluid zone and a solid zone. Velocity inlet condition is applied to nozzle exit, and pressure outlet condition is applied to the outlet above the sheet, far behind the cutting front and below the extension. As we can see from the above figure 1, the grid is tightened near the walls where we observe the development of boundary layers, inside which the gradients of temperatures and velocities are important. Elsewhere, the grid spacing is uniform.

The assigned time step was 10^{-5} s and the convergence criterion on the residuals of each equation was less than 10^{-6} .

3 Results and discussions

Leaving the nozzle exit, nitrogen gas travels the stand-off distance; one part of the gas is blocked by the upper surface of the plate, and spreads horizontally. Here, we can observe an intense interaction between gas and sheet metal, which causes high pressure gradients. The other part continues traveling to enter into the kerf and further expands and accelerates, as shown by the pressure and velocity contours of

figures 3 and 4. In figure 4 we can observe also the development of boundary layers at the vicinity of the cutting fronts.

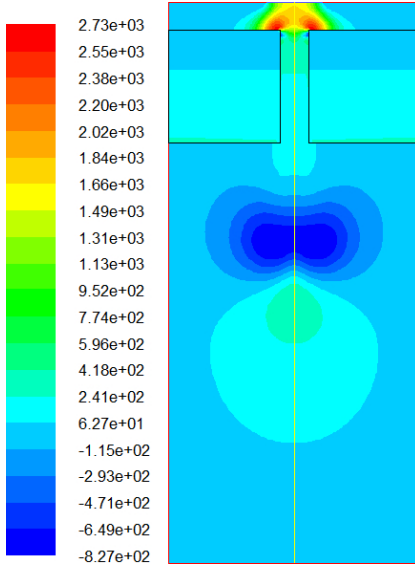


Figure 3: Contours of static pressure at $3 \cdot 10^{-4}$ s

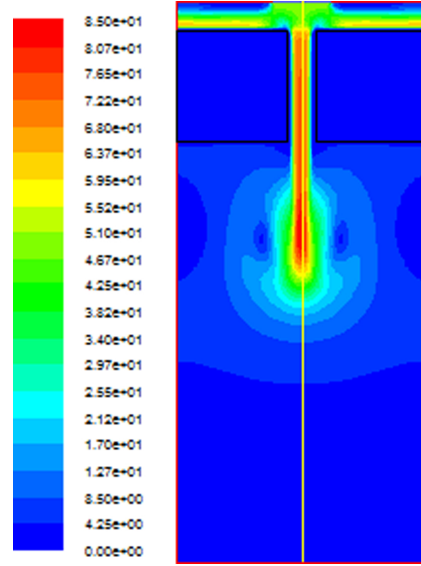


Figure 4: Contours of velocity magnitude at $3 \cdot 10^{-4}$ s

Figure 5 which illustrates the streamlines of the gas along the entire domain (stand-off region + kerf + extension) shows the formation of small cells (vortices) adjacent to the wall in the vicinity of the entrance and a pair of recirculating cells (eddies) which appear in the extension region. Their appearance is essentially due to an abrupt meeting of hot and cold fluids at the entrance and at the exit of the kerf. This approach also allows following the time evolution of the recirculation cells, which shows a downward movement as it can be observed in figure 5 (a, b).

We note that the effect of the vortices formed at the walls lead to the separation of the metallic film from the solid walls as it is illustrated from the volume fraction contours given on figure 6. The vortex motion of the gas prevents the normal flow of the melt film and induces the reverse motion of the latter in the direction opposite to the main flow since the gravity forces are negligibly small.

It was claimed that the molten material cannot be ejected instantaneously after the generation, because a surface tension force retains the material at the top surface when its size is not large enough. The accumulation is considered to start moving when the gas force exceeds the surface tension force. As a result, the film is destroyed in the region of the separation point.

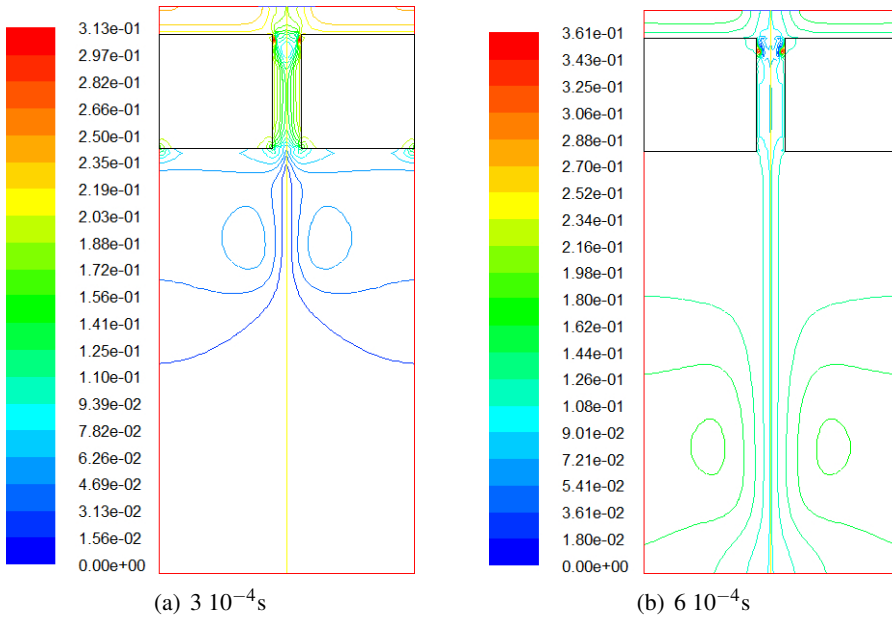


Figure 5: Contours of stream function at two different times.

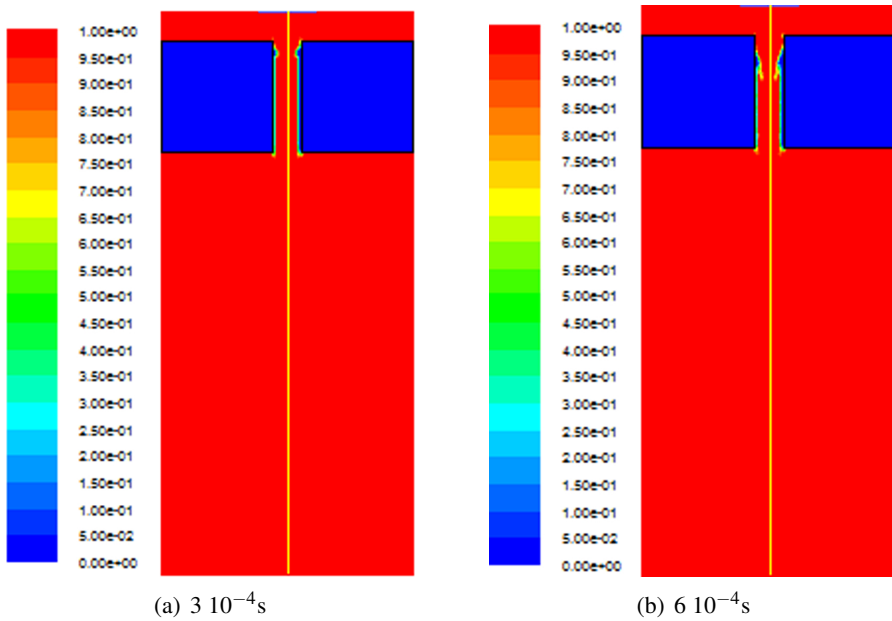


Figure 6: Contours of volume fraction at two different times.

In figure 7, we can see that the outlines of static temperatures show clearly that we are in presence of forced convection boundary layer type, for a subsonic and laminar gas flow since the central part of the kerf remains at 300K. It can also be observed that a part of the absorbed laser power is lost by thermal conduction through the solid part, and cannot thus be used in melting the material, which is the main mechanism to produce a cut. This intense loss of energy by conduction is due to the high conductivity of stainless steel.

Finally, these contours show that these vortices store heat and show the effect of the parietal cells, which create an additional thermal resistance at the walls by avoiding heat transfer and then disturb the whole thermal field of the system.

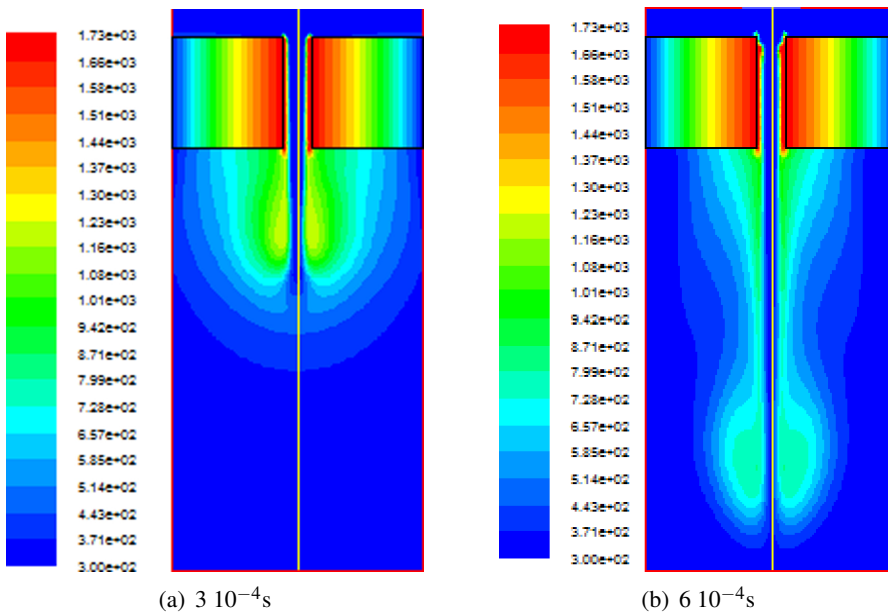


Figure 7: Contours of static temperature at two different times.

4 Conclusion

A numerical study has been conducted to investigate the dynamics of a laminar subsonic nitrogen jet during the application of a laser-fusion cutting technique to a stainless steel sheet. In order to solve the problem properly and to observe the effects, an extended calculation domain of 15 mm length was considered.

The simulation results show that the effects of the vortices formed at the walls can lead to the separation of metallic film from the solid walls, which can significantly

affect the cut quality.

We have observed small vortices and eddies, and we noted that they are responsible of a heat storing effect, which makes them behave as an additional thermal resistance. Such vortices tend to weaken heat transfer and disturb the overall thermal field of the system.

The temperature distribution shows clearly that a part of the absorbed laser power is lost by conduction in the solid part and thus cannot be used in melting the material.

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