Laser fusion cutting: evaluation of gas boundary layer flow state, momentum and heat transfer

M Borkmann, A Mahrle, E Beyer and C Leyens

1 Fraunhofer IWS Dresden, Winterbergstraße 28, D-01277 Dresden, Germany
2 Technische Universität Dresden, Institut für Fertigungstechnik, D-01062 Dresden, Germany
3 Technische Universität Dresden, Institut für Werkstoffwissenschaft, D-01062 Dresden, Germany

E-mail: madlen.borkmann@iws.fraunhofer.de

Keywords: laser fusion cutting, cut edge topography, gas boundary layer, momentum and heat transfer

Abstract

The present work deals with the evaluation of gas boundary layer characteristics under conditions of a high-pressurized gas flow through narrow kerfs as prevalent in laser fusion cutting. A simplistic two-dimensional channel model with appropriate boundary conditions in combination with empirical correlations of the similitude theory is applied to determine the flow state and the thickness of the boundary layer as well as magnitudes of momentum and heat transfer rates. The estimations show that the most expectable flow state of the boundary layer corresponds to a transitional regime. Calculated boundary layer thicknesses lie in a range of 100 to 300 microns after a considered running length of 10 mm. Thus, the formation of the characteristic cut edge topography with typical maximum roughness values for Rz of about 50 microns for high-quality solid-state laser fusion cuts will take place within the boundary layer region. It can be concluded, that the knowledge of the particular spatial and temporal flow structure of the boundary layer should be considered of being indispensable for a profound understanding of the formation mechanisms of the cut edge topography.

List of symbols

| Symbol | Unit | Description |
|--------|------|-------------|
| a      | [m²s⁻¹] | thermal diffusivity |
| Afront | [m²]  | front surface area |
| BL     | [-]   | boundary layer |
| cf     | [-]   | friction coefficient |
| CFD    | [-]   | computational fluid dynamics |
| d      | [m]   | channel or kerf width |
| H      | [m]   | material thickness, channel length |
| Ma     | [-]   | Mach number |
| N₂     | [-]   | nitrogen |
| Nu     | [-]   | Nusselt number |
| P      | [Pa]  | pressure |
| Pr     | [-]   | Prandtl number |
| Q      | [W]   | heat flux |
| q       | [W m⁻²] | heat flux density |
| Rₙ₂    | [J kg⁻¹ K⁻¹] | specific gas constant of nitrogen |
| Rₙ     | [μm]  | roughness value |
| Reₑ    | [-]   | Reynolds number for the core flow, calculated with channel width d |
| Reₜₑ   | [-]   | Reynolds number for the boundary layer, calculated with the BL length |
| T      | [K]   | temperature |
| Tₚref  | [K]   | reference temperature |
| u      | [m s⁻¹] | velocity |
| uₑ     | [m s⁻¹] | core flow velocity |
| z      | [m]   | length of boundary layer |
| α      | [W m⁻² K⁻¹] | heat transfer coefficient |

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decades later, there is still no general consensus about their prevailing physical formation mechanism.

Cut edge roughness needs a profound understanding of the mechanisms that cause these striations. However, of the industrially proven and well established CO2 laser cutting process at a wavelength of 10.6 μm, the cut edge region are the most important criteria for the evaluation of the cutting performance from a technological point of view. Then again, from a scientific point of view, the cut edge topography, often discussed in terms of features such as striations and ripples, have been particularly in the focus of fundamental research. It was very early recognized and stated by Schücker [3] that suitable measures for improvements of the cut quality by reducing the cut edge roughness needs a profound understanding of the mechanisms that cause these striations. However, decades later, there is still no general consensus about their prevailing physical formation mechanism.

Recent work on this topic was largely driven by the advent of high-brightness solid-state lasers at wavelengths of about 1 μm, i.e. fiber and disk lasers and their use for cutting operations. The comparison of cutting results achieved by means of these new and promising laser sources revealed distinct differences to those of the industrially proven and well established CO2 laser cutting process at a wavelength of 10.6 μm. First, higher cutting speeds in thin-section sheets up to 4 mm in thickness can be achieved in solid-state laser cutting but this advantage diminishes for thicker sheets where the cutting speeds are comparable to or even lower than CO2 laser cutting speeds. This dependence could be theoretically reasoned by peculiar differences in Fresnel absorption mechanisms of CO2 and solid-state laser radiation as a function of cut front inclination and angle of incidence, respectively [4–9]. Second, it was observed that solid-state laser cut edges possess higher roughness values in cutting sheet thicknesses above 4 mm and that the cut edge topography obviously looks different from what was usually known from CO2 laser cutting [10–13]. A first comprehensive characterization scheme of CO2 laser cut edges was developed by Zefferer [14]. He distinguished three different surface characteristics, namely ripples of first, second and third kind as vertical structural features of CO2 laser cut edges in stainless steel cutting. Whereas ripples of first kind are represented by depth variations of the solid surface structure, the ripples of second and third kind are formed by re-solidified melt. In case of thick-section steel sheets, the different ripple types typically appear one after the other as the cutting depth increases, i.e. ripples of first kind appear at the upper edge, followed by ripples of second and then third kind. Thus, CO2 laser cut edges typically possess—as a function of sheet thickness, material and processing variables—two or three different horizontal zones of particular height. Such an empirical division in horizontal zones, i.e. zones that seem to be strictly aligned parallel to the upper sheet edge, is also very obvious for a characterization of solid-state laser cut edges. E.g., Hilton [15] identified three different edge sections in disk laser cutting of stainless steel with a thickness of 6 mm. A first section of about 1 mm in depth at the top of the cut showed no striations at all. Below this, a section of about 2 mm in depth was described, where the striations abruptly became visible. Then, a third layer appeared along the remaining thickness that showed a different striation pattern in distinction to the second layer. In case of fiber laser cutting of 18 mm 316L stainless steel sheets, Hu et al [16] showed that the striation characteristics significantly changes in vertical directions and gives rise to four regions with a different appearance. By evaluating cut edges in fibre laser cutting 304 stainless steel sheets with 10 mm in thickness, Borkmann et al [17] even distinguished five different zones in good-quality cuts, where the principal striations are almost vertically formed. For the individual zones different characteristic striation wavelengths were reported. Surprisingly, additional secondary structures were found in the form of small cavities of 10–30 μm diameter and heaps of resolidified melt with a spirally shaped surface structure.

Up to date, no solid theory being capable of explaining such sophisticated cut edge structures is available. However, different hypotheses about possible formation mechanisms were already derived as a result of various research works in the past. In one of the first approaches, Vicanek et al [18] linked the striation formation in laser fusion cutting to stability aspects of the laser-induced melt flow. They distinguished different processing regimes
with dominant shear stress or pressure gradient effects on material removal. A conducted stability analysis of their dynamic melt ejection model revealed instabilities for a pressure gradient controlled melt removal, and it was argued that these instabilities correlate with ripple formation patterns on the cut edge surface. Olsen [19] stated that heat flow fluctuations through the molten layer cause corresponding fluctuations in local melt front velocities. Being located at the side of the kerf, those fluctuations will result in cut width variations, which will be identified as striations of the resultant cut edge. It was also suggested that material evaporation in the lower central part of the kerf is able of forcing the melt partially to the sides and reduces in this way the cut quality. Schulz et al [20] described the dynamical behavior of the laser beam fusion cutting process in terms of the evolving cutting kerf and the melt flow as a free boundary problem by use of integral methods. In particular, the formation of the ripples of first kind without noticeable re-solidified materials is discussed in detail. They concluded that the time-dependent movement of the width of the cutting front as a response to unavoidable fluctuations of the processing parameters causes the onset of ripple formation at the cut edges. Hirano and Fabbro [21] gave a detailed overview over the several types of mechanisms that have been so far theoretically suggested to explain the striation generation in inert-gas steel cutting, including (i) external fluctuations of operating parameters such as laser power and gas flow rate, (ii) hydrodynamic instabilities induced in the melt layer during its interaction with the gas flow, and (iii) instabilities of the thermal dynamics. Hirano and Fabbro [22, 23] also performed extensive experimental investigations on disk laser cutting stainless steel and identified periodical generations and downward displacements of melt accumulations at the cut edges. Also the stability of the central cut front melt flow was discussed as a factor for the final surface roughness. Other experimental studies applied the so-called trim-cut technique to visualize the melt flow under approximated cutting-like conditions. Yudin and Kovalev [24, 25] revealed by corresponding high-speed camera observations that the primary part of the melt flows down at the kerf sides in strokes, rivulets and droplets in a certain distance to the cutting front. Ermolaev et al [26] performed comparative trim-cut trials with CO2 and fiber laser radiation and indicated fundamental differences in the process characteristics. A very comprehensive overview of the different stages of the development of the trim-cutting technique was recently given by Arntz et al [27–29] who used this technique to analyze the melt flow dynamics in fibre laser cutting and demonstrated a possible impact of multiple reflections on striation formation. Recently the melt ejection and dross formation at the bottom side of the kerf was investigated by Stoyanov et al [30] and Pacher et al [31].

The mentioned experimental investigations brought very interesting insights into the dynamics of striation formation. However, underlying cause-effect relationships remain far from being fully understood. In particular, the role of the cutting gas flow and its impact on the development of the final striation pattern on cut edges remain vague. Recent results on fiber laser cutting stainless steel by Borkmann et al [32] revealed a surprisingly close correlation between measured roughness values and computed characteristics of simulated cut edge shear stress distributions. Consequently, it seems to be worthwhile to immerse deeper into investigations about the possible influence of gas flow dynamics on the observed complex cut edge topography.

Research on gas flow aspects in laser fusion cutting with high-pressurized gas jets also has already a long-time history. Fieret et al [33] already gave a comprehensive overview of the underlying physics, the structure of free gas jets and the influence of various nozzle types on the resultant flow distribution. Vicanek and Simon [34] developed a theoretical model to evaluate the forces of the gas jet on the molten layer under laser cutting conditions. They concluded from their calculations that the blow out of the melt is a result of two driving effects, namely the pressure gradient and the shear stress due to friction, both being found of the same order of magnitude. Petring et al [35] experimentally investigated the flow structure in free gas jets as well as in interaction with transparent model kerfs by means of the Schlieren technique. They described the structure of the supersonic flow within the kerf and pointed out that the interaction between the core gas flow and the
boundary layer might influence the melt flow and result in instabilities causing irregular cut edge structures. Zefferer et al [36] linked the detected shock structures of the gas flow within modelled kerfs to distinct and horizontally aligned lines commonly observable at standard CO₂ laser cut edges. They also investigated the influence of gas pressure and nozzle type on the position of the so-called boundary layer separation point, i.e. the location where the core flow is found to be separated from the cut front or edge boundary. This macroscopic flow phenomenon is usually considered of being responsible for a clearly observable melt ejection failure in laser fusion cutting that gives rise to recast and dross problems at the base of the cut [37, 38]. Over the time, also many experimental and numerical investigations were conducted on the performance of different nozzle types, e.g. by Masuda and Moriyama [39], Man et al [40], and Kovalev et al [41]. A very comprehensive review on the influence of the cutting gas flow on characteristics in laser beam fusion cutting was recently compiled by Riveiro [42].

Discussed are (i) the macro structure of the supersonic gas jet as a free stream as well as in interaction within cut kerf models, (ii) the role of the boundary layer separation point for melt removal, and (iii) the influence of different nozzle types on the efficiency of melt removal. They concluded that the interaction between gas and molten film is of vital importance and that advanced CFD simulations and new theoretical and experimental approaches are required to deepen the understanding of corresponding effects.

Because the numerical efforts for advanced CFD simulations are thought of being immense for corresponding simulations, this work is initially dedicated to an analytical characterization of the principal properties of the developing boundary layer at cut edges under conditions of a high-pressurized cutting gas flow through a narrow kerf. It will give first estimations about the expected boundary layer flow state, the relevant factors that cause the transition from a laminar into a turbulent regime, the boundary layer thickness, as well as characteristic numbers for momentum and heat transfer. As a result, this analysis will provide data that might be useful for an adequate modelling and numerical simulation of the gas boundary layer in laser fusion cutting to resolve its particular spatial and temporal flow structure.

2. Physical description of the cutting gas flow

As already mentioned, in laser fusion cutting a high-pressure inert gas is coaxially arranged to the laser beam to eject the molten material. Commonly, nitrogen at pressures between 0.5 and 2.0 MPa is used as a cutting gas. In general, the diameter of the mainly applied conical nozzles clearly exceeds the width of the cut kerf and especially at low nozzle-material distances up to 1.0 mm almost constant gas conditions result at the nozzle center. The ratio of the gas pressure to the ambient pressure clearly exceeds the critical pressure ratio of 1.89 and a supersonic gas jet is formed. Figure 2(a) depicts a Schlieren picture of a flow through a cut kerf model made of glass to reveal its macrostructure under adiabatic conditions of non-heated, i.e. cold surfaces.

Due to the high pressure ratio the gas is massively expanded and accelerated. The gas flow exceeds sonic speed and a complex 3D structure of compression shocks and expansion fans develops. In figure 2(b) a simulated velocity distribution under consistent boundary conditions according to figure 2(a) is shown. The commercial CFD-Code FLUENT and Reynolds-averaged-Navier–Stokes equations with an appropriate turbulence model and standard wall functions were used in the simulation. A detailed description of the
numerical model can be found in [32]. Obviously, the simulation results show a high level of agreement with the experimentally recorded flow distribution, and it can be concluded that the gas flow simulation provides reliable results. The detected gas flow separation at the cut front, as clearly recognizable in the experimental and numerical results as well, was already linked to a macroscopic melt ejection failure in practical laser fusion cutting experiments causing increased amounts of recast and dross at the base of the cut. Then again, the macrostructure of the gas flow is however not capable of resolving the flow structure within the gas boundary layer that might play a vital role for the cut edge topography.

3. 2D channel model of the cutting gas flow

The formation and development of a boundary layer (BL) by a fluid flowing over a solid surface has been a subject of intensive fundamental and applied research for decades [43]. Figure 3(a) schematically shows the development of the BL from a laminar to a turbulent flow state for the case of a fluid flow over a flat surface and a turbulent core flow. At first, the BL is very thin and laminar. At some distance \( z \) to the leading edge, conditions are changing by developing instabilities. The BL becomes turbulent with high mixing grades normal to the wall and the BL dramatically grows in thickness. The transition process and the ongoing production of turbulence within the boundary layer are governed by large scale coherent vortex structures which affect the local distributions of shear stress and heat flux at the wall. Semi-empirical equations are available which allow predictions about the flow state (laminar vs. turbulent) of the BL, as well as a quantification of corresponding momentum and heat transfer rates.

For this purpose and in first approach, the complex three-dimensional gas flow in laser fusion cutting is approximated by a 2D channel model with vertical cut edges as shown in figure 3(b). The assumption of parallel side walls is supposed to be applicable in the case of larger material thicknesses and less focused laser beams. Despite its simplicity, it is expected by the authors that fundamental and general findings about the boundary layer development can be drawn. The 2D model geometry relies on the definition of a cross section of the kerf at the junction of the front and side walls. It is defined by a constant distance \( d = 0.8 \text{ mm} \) between the parallel walls and a height \( H = 10 \text{ mm} \) that corresponds to an exemplary sheet thickness separated by means of laser fusion cutting.

Nitrogen as the preferred gas in laser fusion cutting is considered as an ideal gas with the specific gas constant \( R_{N_2} = 296.8 \text{ J/(kg K)} \). The flow velocity and pressure at the inflow boundary are considered of being constant. This assumption can be well justified by the fact that the diameter of the used gas nozzles in laser fusion cutting is typically much larger than the kerf width. Furthermore, the estimation also requires a constant flow rate through the kerf over the entire kerf depth. Two limiting flow states are evaluated to cover the entire range of conceivable gas states in laser fusion cutting as extracted from gas flow simulations of the core gas flow under cutting.
conditions as shown in figure 2(b). The first flow state (State I) is defined by the inflow condition at the top of the kerf with high gas pressure $P_0$ and a high but still subsonic velocity $u$. The second flow state limit (State II) relies on the outflow condition with the pressure $P_1$ at the outlet of the channel that roughly corresponds to the ambient pressure and a supersonic velocity corresponding to a Mach number of $Ma = 2$. Related boundary conditions and gas properties are listed in table 1. Here, the density values are calculated according to the general gas equation of ideal gases:

$$\rho_{N_2} = \frac{P}{R_{N_2} \cdot T}$$

for a reference temperature of 293 K. The reference value of the dynamic viscosity was borrowed from gas property tables given by Jeschar et al [44].

Using the given values, the Reynolds number as the principal dimensionless number of the similitude theory to characterize the state of a flow can be calculated for the core flow according to its definition as ratio of inertial to viscous forces:

$$Re_d = \frac{u \cdot \rho \cdot d}{\eta}$$

with the flow velocity $u$, the gas density $\rho$, the kerf width $d$ as characteristic length and the dynamic viscosity $\eta$. A Reynolds number value of $Re_{d,\text{crit}} \approx 2300$ is typically given as a critical value for a transition from a laminar to a turbulent flow regime for tube and channel flows. Both of the defined flow conditions at the inlet and the outlet of the kerf lead to Reynolds numbers that are much larger than this threshold value. In case of the inlet (State I) one gets $Re_{d,0} = 1.75 \times 10^5$, and for the outlet (State II) a Reynolds number of $Re_{d,P_1} = 3.3 \times 10^5$ is calculated. Thus, the channel core flow will be of turbulent nature.

Most interesting for an evaluation of the developing boundary layer at the cut edge are its flow state and thickness, as well as estimations of the expectable momentum and heat transfer rates between edge surface and gas. Due to the fact that the edge surface is strongly heated under cutting conditions by the incident laser beam, the analysis is principally performed under conditions of a heated and high-temperature wall.

The flow state of the boundary layer and its thickness are dependent on the local position $z$ along the overflowed surface (figure 3(a)). Respectively, the Reynolds number of the boundary layer $Re_z$ is not defined for a constant value of a characteristic length like the Reynolds number $Re_d$ of the core flow but depends on the position $z$ along the overflowed solid surface:

$$Re_z = f(z) = \frac{u \cdot \rho(T, z) \cdot z}{\eta(T)}$$

A critical value $Re_{z,\text{crit}} \approx 3 \times 10^3$–$5 \times 10^3$ is reported for the transition to a turbulent state for the flow over a flat plate with sharp leading edges. In case of an unshapely leading edge as might be more characteristic in laser fusion cutting, the critical Reynolds number can be even reduced to a critical value of $Re_{z,\text{crit,min}} \approx 3 \times 10^4$.

Due to the thermal nature of the cutting process also a thermal boundary layer develops which in turn affects the boundary layer flow as a result of the inherent heat transfer between the cold gas and the hot cut edge surface. The temperature of the liquid melt layer in laser fusion cutting must be lying between the melting and boiling point of the material, i.e. between 1800 K (1530 °C) and 3000 K (2730 °C) in case of iron or ferrous alloys, respectively. To facilitate the analysis, an average and constant value of 2500 K (2230°C) is assumed for the whole cut edge surface. The assumption of this value of temperature magnitude is not only justified by the empirical process understanding but also by experimental temperature measurements of the cut front interface during laser fusion cutting of stainless steel [45]. Such a thermal boundary condition causes a temperature distribution throughout the boundary layer with a gas temperature of 2500 K at the wall, i.e. cut edge surface, and the temperature of the core flow (roughly ambient temperature, i.e. $\approx 300$ K) at the outer edge of the thermal boundary layer. In such a case, the temperature dependence of density and viscosity can play an important role for the boundary layer development and must be considered [46]. Calculated values of the density as a function of temperature and pressure according to the state equation of ideal gases, as well as values of the dynamic

| Quantity   | Symbol | Dimension | State I | State II |
|------------|--------|-----------|---------|----------|
| Pressure   | $P$    | MPa       | 1.6     | 0.1      |
| Velocity   | $u$    | m s$^{-1}$| 200     | 600      |
| Density    | $\rho$ | kg m$^{-3}$| 18.4    | 1.15     |
| Viscosity  | $\eta$ | Pa s      | $16.8 \times 10^{-6}$ | $16.8 \times 10^{-6}$ |

Table 1. Reference values of for the defined flow states $P_0$ (state I) at the top of the kerf and $P_1$ (state II) at the outlet.
viscosity as a function of temperature according to a power approach given again by Jeschar et al.\textsuperscript{[44]} are shown in figure 4.

Because the thermal boundary layer thickness of gases with Prandtl numbers \( \text{Pr} = \nu / \alpha \approx 1 \) (ratio of kinematic viscosity \( \nu \) to thermal diffusion \( \alpha \)) is similar in magnitude to the thickness of the flow boundary layer, it seems to be sufficiently justified to assume an average reference temperature of \( T_{\text{ref}} = 1400 \text{ K} \) to characterize the thermal state of the flow boundary layer. With this assumption, boundary layer Reynolds numbers can be calculated as a function of the position along the kerf surface according to equation (3).

A very important quantity of the boundary layer that can be calculated as a function of the resulting Reynolds number values \( R_z \) is the thickness \( \delta \) of the boundary layer. Distinguishing between laminar and turbulent flow regimes, Schlichting and Gersten\textsuperscript{[43]} recommended the following approximations:

\[
\delta_{\text{lam}}(z) = 5.0 \cdot z \cdot \text{Re}_z^{-0.5} \\
\delta_{\text{turb}}(z) = 3.7 \cdot z \cdot \text{Re}_z^{-0.2}
\]

The local momentum transfer between cut kerf edge and gas flow that plays the most crucial role with regard to the blow out of molten material in real fusion cutting experiments, also depends on the boundary layer flow state. Corresponding shear stresses can be calculated as a function of local friction coefficients \( c_f(z) \). Introducing the friction coefficient functions as derived for a flow over a plane surface by Schlichting and Gersten\textsuperscript{[43]}, one gets the following equations for the wall shear stresses \( \tau_{W,\text{lam}} \) and \( \tau_{W,\text{turb}} \) in case of laminar and turbulent boundary layer flow states:

\[
\tau_{W,\text{lam}}(z) = c_{f,\text{lam}}(z) \cdot \rho_{\text{dyn}} = 0.664 \cdot \text{Re}_z^{-0.5} \cdot \frac{\rho}{2} \cdot u_{\infty}^2 \\
\tau_{W,\text{turb}}(z) = c_{f,\text{turb}}(z) \cdot \rho_{\text{dyn}} = 0.0592 \cdot \text{Re}_z^{-0.2} \cdot \frac{\rho}{2} \cdot u_{\infty}^2
\]

The heat transfer rates between the gas and the cut edge surface can be estimated by applying well-known equations for the Nusselt number \( \text{Nu} \) as a function of boundary layer Reynolds number \( \text{Re}_z \) and the Prandtl number \( \text{Pr} \). To facilitate the analysis, only mean values over the overall flow length, i.e. the kerf height \( H = 10 \text{ mm} \), are calculated. Corresponding equations are given by Baehr and Stephan\textsuperscript{[47]} for the case of a flow over a plate. Under conditions of a laminar BL, the corresponding relation for the Nusselt number can be analytically derived:

\[
\text{Nu}_{\text{Mean, lam}} = 2 \cdot \text{Nu}(z = H) = 0.664 \cdot \text{Re}_z^{1/2} \cdot \text{Pr}^{1/3}
\]

In case of a turbulent BL, an empirical correlation equation by Gnielinski\textsuperscript{[48]} is recommended. It reads as follows:
The heat transfer for transitional states of the boundary layer is then considered as a mixed regime and the corresponding Nusselt number can be approximated by a quadratic blending function:

$$\text{Nu}_{\text{Mean, turb}} = \frac{0.037 \cdot \text{Re}^{0.8} \cdot \text{Pr}}{1 + 2.443 \cdot \text{Re}^{-0.1} \cdot (\text{Pr}^{2/3} - 1)}$$

The given equations allow an estimation of the heat transfer coefficient $\alpha_{\text{Mean}}$ according to the definition of the Nusselt number:

$$\alpha_{\text{Mean}} = \frac{1}{H} \cdot \text{Nu}_{\text{Mean, turb}} \cdot \lambda_{\text{N}_2}$$

with $\lambda_{\text{N}_2}$ as the heat conductivity of nitrogen. Assuming that the kerf front can be considered of being a half cylinder with a diameter $d$ that corresponds to the kerf width $d$ and a height $H$, the overall heat flux $Q$ from the heated front surface to the gas flow follows to:

$$\dot{Q} = \dot{q}_{\text{Mean}} \cdot A_{\text{front}} = \alpha_{\text{Mean}} (T_w - T_c) \cdot \pi \cdot \frac{d}{2} \cdot H$$

With this set of semi-empirical equations, tentative estimations of the BL flow state, BL thickness and momentum and heat transfer can be prepared for the gas flow in laser fusion cutting under the mentioned assumptions.

4. Results and discussion

4.1. Boundary layer flow state and thickness

Boundary layer Reynolds numbers $\text{Re}_z$ can be calculated as a function of the position along the kerf surface according to equation (3). Figure 5 shows the resultant dependencies for an adiabatic ($T_{\text{wall}} = T_{\text{ref,gas}} = 300 \text{ K}$) and a strongly heated surface ($T_{\text{wall}} = 2500 \text{ K}$, $T_{\text{ref,gas}} = 1400 \text{ K}$) in graphical context with the mentioned critical Reynolds numbers $\text{Re}_{z,\text{crit}}$ and $\text{Re}_{z,\text{crit,min}}$. It becomes clear that the consideration of the thermal state of the boundary layer strongly affects the position at which the laminar boundary layer is prone to turn into a turbulent stage. In case of a cold material (or an adiabatic wall), the transition already occurs at the top of the kerf. At about $z = 2 \text{ mm}$, the defined critical Reynolds number range is exceeded and a turbulent flow boundary layer is predicted for the remaining kerf region. In contrast, if the heat transfer to the gas is considered — and that might be regarded as realistic condition with respect to laser fusion cutting — the predicted state of the flow boundary layer changes: Due to the decrease of the density and the increased viscosity at elevated temperatures, the corresponding Reynolds numbers of the BL are decreased by more than one order of magnitude. In that case, the Reynolds number is initially well below the minimum critical value of $\text{Re}_{z,\text{crit,min}}$ and at least the upper 2 mm of the BL are predicted of being in a laminar state. This means that this part of the BL is stable and perturbations should be attenuated. For higher depths, the calculated Reynolds numbers still remain in the lower range of the
critical zone and the flow state is potentially transitional between the laminar and the turbulent flow regime. Although the BL might become unstable and perturbations will probably no longer effectively be attenuated, it is probable that the amplification of disturbances remains small due to the moderate Reynolds numbers. In any case, the length of the transition process to a fully turbulent flow state will be enlarged.

Calculated values of the boundary layer thickness $\delta$ for laminar and turbulent flow states for the relevant case of a heating wall are displayed in figure 6. For the sake of simplicity, it is assumed that the turbulent BL is also just starting at the upper corner of the channel edge. It is obvious that the thickness of the turbulent BL grows much faster than that of the laminar BL. At $z = 10 \text{ mm}$ a turbulent BL reaches a thickness of $250 \mu\text{m}$ to $340 \mu\text{m}$ whereas a laminar BL is predicted being only $60 \mu\text{m}$ to $120 \mu\text{m}$ thick. That means that the boundary layers of the opposite cut edges of an assumed kerf width of $800 \mu\text{m}$ are not supposed to meet each other over the considered height $H$ of the kerf, i.e. the assumption of independent opposite boundary layers is justified. Furthermore, analogy approximations of the well investigated case of a flow over a flat plate—as given in the model description—are applicable for a characterization of related coefficients of momentum and heat transfer.

### 4.2. Momentum and heat transfer

Calculated local friction coefficients and resultant local wall shear stress values according to equations (6) and (7) are depicted in figure 7 for the both limiting flow states and a heated wall as a function of the $z$-coordinate. Comparable shear stress values for the laminar and turbulent flow state in the range of $3000–4000 \text{ Pa}$ are prognosticated for the top part of the channel for $z \leq 1 \text{ mm}$ only. For higher $z$-values, the magnitudes of wall shear stress become clearly distinguishable. In consistency with theoretical expectations, the values of friction

![Figure 6](image-url)

Figure 6. Local boundary layer thickness for laminar and turbulent states of the heated boundary layer. Heat transfer and temperature dependent gas properties are considered.

![Figure 7](image-url)

Figure 7. Local friction coefficient (a) and local wall shear stress (b) as a function of $z$-coordinate for different flow conditions.
 coefficient and wall shear stress are larger for a turbulent state of the boundary layer. It is worthwhile to emphasize the fact that the estimated wall shear stresses—despite the large pressure and density differences between the both considered limiting flow states—are primarily influenced by the boundary layer flow state. Correspondingly, the calculated value ranges appear as well-distinguishable narrow bands for the laminar and turbulent BL flow state. The calculated high shear stress values at the top of the kerf dramatically decrease downwards within the first 2 mm with a steeper loss of shear stress magnitude in case of the laminar BL. For larger z-coordinates, the shear stress of a turbulent BL is approximately twice as high as for a laminar BL. In the region of the defined outlet for $z = 10$ mm, a laminar BL generates shear stresses of 800 Pa, whereas a turbulent BL is still capable of exerting up to 2000 Pa. These calculated shear stress values correspond very well to numerically computed maximum axial shear stress values of a cutting gas flow CFD analysis [32].

Calculated values of heat flux density $\dot{q}$ and overall heat flux $\dot{Q}$ are shown in figure 8 for the different boundary layer flow states under consideration of the limiting boundary conditions. Apparently for all flow states, the heat transfer for the gas condition at the top of the kerf is more than twice as intensive as the one for the bottom condition. Hence, a notably higher heat transfer at the entrance region of the kerf can be expected. Furthermore, for a transitional or turbulent boundary layer, the heat transfer is doubled in comparison to laminar boundary layer conditions. For the used value of an averaged cut front temperature of about $2200 \, ^\circ C$ a total heat transfer loss of 24–114 W is estimated. In conventional laser fusion cutting, e.g. with 4 kW laser power for cutting of 10 mm stainless steel and an experimentally determined coupling efficiency of about 50% [49] this loss corresponds to less than 3% of the applied laser power or to less than 6% of a absorbed laser power, respectively. These contributions seem to be insignificant.

5. Summary

In laser fusion cutting the combined action of laser beam and inert cutting gas flow produces a 3D cut kerf geometry with locally varying kerf width and front inclination. The applied high pressure supersonic gas jet is characterized by a complex 3D flow structure of compression shocks, expansion fans and there interactions. After decades of industrial application and scientific investigations the involved physical mechanisms especially concerning the melt driving forces are still not fully understood. Since the interface between gas and melt flow is crucial for the acceleration and removal of melt this work gives tentative estimations of basic gas boundary layer properties. The developed analytical 2D model for the gas flow in laser fusion cutting is based on the following assumptions and approximated flow conditions:

- 2D channel model with parallel walls, 10 mm in length and 0.8 mm in width
- constant base flow conditions along the channel, i.e. pressure chances and acceleration of the gas are disregarded
- consideration of flow condition state I (inflow at high pressure and low velocity) and state II (outflow at ambient pressure and supersonic velocity) as approximate thresholds of the actual flow
• adiabatic wall or constant wall temperature of 2500 K
• Nitrogen as ideal gas with density, pressure and temperature according to general equation of state and temperature dependent viscosity according to Jeschar et al [44]

The assumptions made allow for the applicability of the semi-empirical equations and relationships from the similitude theory.

The study revealed that the heat transfer from the wall to the cutting gas has a crucial impact on the gas boundary layer flow state and its development along the cutting front and cut kerf edge, respectively. In an adiabatic case with constant gas properties at ambient temperature, an almost completely turbulent boundary layer is predicted with an early transition to a turbulent state at the top of the kerf. In contrast, if more realistic thermal boundary conditions and temperature-dependent gas properties are considered, the boundary layer is initially found to be laminar and becomes susceptible for perturbations just after some millimeter distance from the leading edge. But the analysis also suggests that the transition process to a turbulent flow regime is very elongated with weak amplification of instabilities.

Subsequently, the estimations of derived quantities like boundary layer thickness, wall shear stress and heat transfer differ between the principal flow states. For a completely turbulent boundary layer a thickness of up to 340 μm is predicted whereas a laminar boundary layer is just 120 μm thick after 10 mm flow over the surface or cut edge, respectively. The presumed transitional boundary layer is thought to be in between but only slightly larger than the laminar case due to the attenuation or weak amplification of instabilities. For all BL flow states shear stresses higher than 3000 Pa are estimated for the first millimeter of cut edge. The area of high shear stresses corresponds well to the uppermost section at the cut edge where striations as depth variation of the base material without resolidified melt were described by Zefferer [14] and Borkmann et al [17]. Considering that high shear stresses facilitate an effective removal of the melt this coincidence seems to be expectable. The current BL flow state is especially essential for the calculated local shear stresses for material thicknesses over 2 mm. The average momentum transfer at z = 10 mm for a transitional or turbulent BL reaches values up to 2000 Pa and is twice as large as the shear stress of a laminar flow state. An effect of the BL flow state is also seen with respect to prognosticated heat transfer rates. Additionally, an even more pronounced effect of the base flow conditions is detected. Higher heat flux rates are found at the top of the kerf and a decrease of local heat flux rates with increasing z-coordinate is expected. Nevertheless, both the estimated heat flux densities and the overall heat flux values are relatively small and should be negligible in comparison to the intensities and powers of high-power laser beams usually applied and absorbed in thick-section metal sheet cutting.

6. Conclusions

At least for two different scopes sweeping conclusions can be drawn from the results of this study. The first one concerns the modelling and simulation of laser cutting processes. Despite of sophisticated models for absorption and reflection of the laser beam, resulting temperature distributions, the melting of the material and the melt flow, commonly the gas flow is highly simplified in processing models, e.g. to low velocities, reduced to a simplistic boundary condition derived from analytical assumptions or even disregarded at all. Actually this work emphasizes the strength of impact and possible variety of gas flow features and boundary layer development even for a gas model at this high level of simplicity. Hence some recommendations concerning gas flow consideration for more realistic modelling and simulation of laser cutting processes can be given:

• realistic boundary conditions for pressure and temperature
• modelling of viscous terms and resolution of boundary layer development
• temperature dependent gas material properties

Considerably, as a result of this analysis it can be concluded that an engagement with the characteristics of gas flow and boundary layer development in modelling of laser fusion cutting has the potential to upgrade the level of process understanding.

A second application area is the analysis and interpretation of experimental cut edge structures. Commonly the cut edge topography is considered as result of an inherent instability of the melt flow. Proceeding from the present work an alternative interpretation by means of boundary layer development is reasonable. It is worthwhile to note that the roughness values Rz (average height difference between the highest peak and the lowest valley) of good quality fiber or disk laser cuts in stainless steel sheets with a thickness of 10 mm are typically lying in a range of between 30 and 60 μm in dependence on the distance of the actual measurement position to the top edge. Thus, it can be concluded from the performed analysis that the interaction between
melt film and gas as well as the formation of the particular structure of the cut edge clearly takes place within the boundary layer region. The fact that a transitional boundary layer with a weak amplification of instabilities is predicted has a far-reaching impact on structure and development of the boundary layer. During the transitional flow state coherent vortices develop in the BL in consequence of the instability of the BL. These vortices govern momentum and heat transfer at the wall and lead to growing average shear stresses and heat flux densities. It has to be considered that the presented analysis only provides integral estimations of the expectable magnitudes of the calculated quantities. Actual local distributions of shear stress and heat flux at cut edge surfaces will be strongly affected by characteristics of the boundary layer development under process conditions of narrow and inhomogeneously heated kerf surfaces and high spatial pressure and velocity gradients of the core flow. Thereby, as proven by experimental investigations, the local transitional heat flux and shear stress can overshoot turbulent values up to 50% [50] due to the high degree of regularity of the vortex structure in the transitional BL. Highly expectable is a strong impact of the processing conditions in laser cutting on the kind of evolving instability modes and corresponding vorticity properties and hence on the actual local distributions of shear stress and heat flux [51–53].

Due to a lengthy transitional boundary layer with weak amplification, coherent vortices of primary and secondary instability modes probably have abundant opportunities to imprint their structure into resolidifying melt remains due to locally varying shear stresses and heat fluxes. Especially in case of stationary respectively non-moving vortices it should be possible to draw inferences from the cut edge structure about the vortex structure of the boundary layer. In figure 9 a high-resolution microscopic picture of a good quality cut edge for fiber laser cutting in 10 mm stainless steel and a detailed view of the bottom part in true color and as elevation map are shown. The whole cut edge is characterized by a very regular pattern of almost vertical striations. Within the first millimeter at the top the horizontal wavelength of the striations is very small and about 125 μm. Towards the bottom the wavelength increases to about 200–300 μm but is still very regular. In the detailed view from the bottom half and the elevation map spirally shaped heaps lined up at one side of the striations are clearly

Figure 9. High resolution microscopic picture of a good quality cut edge for fiber laser cutting in 10 mm stainless steel and detail from the bottom half in true color and as elevation map.
identifiable. Notably at the left kerf side they are located at the right side of a striation crest and rotate anticlockwise inwardly while at the right kerf side the location and behavior are inverse. Anticipating that the cut edge topography results as imprint of the boundary layer vortex structure these experimental findings show a high resemblance to primary and secondary instability modes of a crossflow instability, e.g. numerically determined by Bonfigli and Kloker [54]. Prospectively, the interpretation of the resultant cut edge by means of boundary layer development at least should broaden existing explanation approaches.

Acknowledgments
The work was in parts financially supported by the German Research Foundation DFG within the project ‘Evaluierung dynamischer Lösungsansätze zur Optimierung des Inertgasschneidens von Dickblech mit Laserstrahlquellen hoher Strahlqualität’, Contract No. BE1875/36-1. This support is highly appreciated by the authors.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs
M Borkmann  https://orcid.org/0000-0002-1182-0245
A Mahrle  https://orcid.org/0000-0001-9190-6999

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13
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