Laser cutting of metal laminates: analysis and experimental validation

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Abstract

Laser cutting has been investigated for a number of aluminum–synthetic laminates, newly developed materials for the aeronautic and automotive industry. The materials consist of alternating aluminum and synthetic layers. It is shown that these materials can be cut at the same speed as homogeneous aluminum alloys, although some damage on the synthetic layers has to be accepted. Based on these experimental results, a dedicated computer simulation model has been developed. The applied cutting model is based on splitting the material in several horizontal layers, each with its own specific thermophysical and optical properties. The separate layers are coupled by known mass, power and force balance equations. Some hypotheses are formulated about the synthetic layer damage, which are evaluated analytically. Finally, the model results are experimentally evaluated.

Keywords: Laser cutting; Laminates; Hybrid material; Modeling; Experimental validation

1. Introduction

The introduction of metal laminates in industry offers many challenges as well for design as for production engineering. These materials are typically aluminum-based, with an aluminum sheet thickness in the order of 0.25 mm. Up to six aluminum sheets may be encountered in one laminate, which are filled up with a synthetic material, such as epoxy embedded glass or aramid fibers, or polypropylene. The total material thickness is typically in the range 1–3 mm. There is a vast amount of possible applications for laminated sheet materials. For instance, application of such materials in cars will result in a major weight reduction, which paves the way for smaller engines and less fuel consumption. In the light of the current environmental issues, this may be of vital importance for the automotive industry. Application of laminates in aeroplanes gives a large enhancement of fatigue resistance, which results in lighter and safer constructions, the two important issues in the aircraft industry. In a nutshell, one can say that application of metal laminates is worth consideration for very light constructions or for constructions that require a very specific property such as high fatigue resistance.

However, traditional machining technologies may be useful for some elements of a laminate, but can be harmful for others. For instance, traditional milling of fiber reinforced materials results in severe fiber pull-out, and serious tool wear. Traditional drilling of laminated materials results in delamination of the lower layers. Among other non-conventional technologies, laser cutting seems to be more appropriate for this operation. Laser cutting has developed over the past years to a reliable, flexible and fast cutting technology for homogeneous materials. Mild steel, stainless steel, aluminum, glass and plastics are relatively easy to cut in practice for several years [3]. However, in the area of non-homogeneous materials a suitable laser cutting technology has not yet been established. Although it is shown that aluminum-based metal laminates can be cut at the same speed as homogeneous aluminum alloys, laser cutting of metal laminates suffers from some drawbacks. Being a thermal cutting technology, the synthetic layers in metal laminates are damaged due to the large difference in thermophysical properties of metals and synthetics [1]. Also some dross attachment is encountered.

In this paper, the physical causes of the synthetic layer damage are investigated by evaluating several physical phenomena in a state-of-the-art model for laser cutting. This model was first introduced by Petring [5] for homogeneous...
metals, and modified for laminated materials in [2]. The results of this model analysis will be experimentally evaluated and used to propose improvements on the laser cutting equipment.

2. Model description

Laser cutting is a thermal process, with a focused high-power laser beam which induces a large heat flux, causing the material to melt and sometimes even to evaporate. The molten material is removed by a strong gas jet, coaxially with the laser beam. As the laser beam moves relatively to the material, a cut kerf is produced. This rather crude description of the laser cutting process still captures the essential phenomena which should be included in a model:

- the characteristics of focused laser light,
- the way in which laser light is absorbed by the material and how it is converted into a heat flux,
- the way in which the applied energy is used to melt or evaporate the material,
- the characteristics of a gas jet,
- the way in which the gas jet interacts with the molten material.

These phenomena are included in the applied laser cutting model, as are the influences from vapor pressure and surface tension. The model is meant for inert gas cutting, which is appropriate for laser cutting of laminates. Here, we will only describe the main features of the applied model. For more detailed information the reader is referred to the above-mentioned publications.

The main characteristic of the model is a division of the material in \( N \) horizontal layers (Fig. 1a). This division in horizontal layers makes the transition to laminated materials very natural. On each slice of material a mass, impulse and power balance is applied, which determines the local kerf geometry. The dimensions of one cut front segment are depicted in Fig. 1b. This figure also shows two important model assumptions: the geometry of the cut front is assumed to be semi-circular and the melt layer is assumed to have an equal thickness \( d_m \) on the entire cut front, from \( \phi = 0 \) to \( \pi/2 \). By coupling all layers a set of equations is obtained, which will be iteratively solved.

2.1. Power balance

The power balance describes the equilibrium between absorbed laser light and the energy needed to create a cut kerf. The local energy balance can be summarized as

\[
AP_L = P_{T_L} + P_m + P_v + P_c
\]

in which \( AP_L \) is the absorbed power generated by laser light, \( P_{T_L} \) the power needed to heat up the material which is to be removed up to the melting temperature, \( P_m \) the power needed for fusion, \( P_v \) the power needed for evaporation and \( P_c \) the power which is lost due to conduction into the base material. The absorbed laser power \( AP_L \) is computed by integrating the product of local laser power density \( I_L \) and local absorptivity \( A(z) \) over the irradiated surface:

\[
AP_L = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} A(z) I_L \cos \alpha \left( \frac{r_e}{\sin \gamma} \right) d\phi
\]

where \( dz \) is the element thickness, \( \theta \) characterizes the local direction of the laser light with respect to the laser beam axis, \( \gamma \) the element inclination, and \( \alpha \) the angle of incidence of laser light, computed from the product of \( \theta \) and \( \gamma \). The local power density \( I_L \) is described by the well-known Gauss–Laguerre TEM modes and the local absorptivity can be computed by evaluating the angle of incidence dependent Fresnel equations:

\[
A_\parallel(z) = \frac{4n \cos \alpha}{(n^2 + k^2) \cos^2 \alpha + 2n \cos \alpha + 1}
\]

\[
A_\perp(z) = \frac{4n \cos \alpha}{(n^2 + k^2) + 2n \cos \alpha + \cos^2 \alpha}
\]

Fig. 1. Layout and dimensions of a cut front segment.
A viscosity, evaluated at the average melt temperature $T_z$ the processing speed $v$, temperatures $T_s$, pressure and atmospheric pressure. The average and surface mass flow caused by the pressure difference between vapor obtained formulas show that these temperatures are solely a dimensional stationary convective–diffusive equation. The material, resulting in a Couette flow in the molten layer. The

$$2.3. \text{Impulse balance}$$

The mass balance is based on the mass fluxes entering and leaving a control volume, which is stationary with respect to the laser beam axis, as shown in Fig. 2. Entering mass flows are the material in front of the interaction zone (first LHS term in Eq. (5)) and the material that enters the control volume from above (second LHS term). Leaving mass flows are the material that leaves sideways, the material that flows downwards to the next segment (first RHS term), and the material that evaporates. For segment $i$ this can be summarized as

$$2\rho v r_n[i] dz[i] + \left( \frac{\pi}{2} \rho s r_w[i - 1] \left( r_n[i] - 1 + \frac{d_m[i - 1]}{2} \right) d_m \right)^2$$

$$\times \left[ \left( \frac{\pi}{2} \rho s r_w[i] \left( r_n[i] + \frac{d_m[i]}{2} \right) d_m \right] + J_v[i] + J_o[i]$$

(5)

where $d_m$ is the melt thickness, $\hat{d}_m$ the melt thickness corrected for the segment inclination and $\eta_m$ the melt viscosity, evaluated at the average melt temperature $T_p$. $J_v$ the mass flow due to vaporization, $J_o$ the additional sideways mass flow caused by the pressure difference between vapor pressure and atmospheric pressure. The average and surface temperatures $T_p$ and $T_s$ are obtained by solving the one-dimensional stationary convective–diffusive equation. The obtained formulas show that these temperatures are solely a function of melt layer thickness $d_m$, material properties and the processing speed $v_s$.

$$2.2. \text{Mass balance}$$

$$2.3. \text{Impulse balance}$$

The gas in the cut kerf causes a shear stress on the molten material, resulting in a Couette flow in the molten layer. The cut gas velocity $v_{gs}$ can be computed as a function of the gas properties and the pressure inside the nozzle. Of course, the velocity of the cut gas varies a little as it travels through the cut kerf, as will its pressure. However, the velocity variations which results from the pressure variations are small compared to the overall cut gas velocity. From a modeling point of view, we consider the velocity of the cut gas as constant in the cut kerf. This implies a constant atmospheric pressure. These assumptions typically results in velocities of about 500 m/s for a cut gas pressure in the range 1–2 MPa (N2).

The shear stress $\tau_w$ which is caused by friction of the gas jet on the melt layer follows from

$$\tau_w = \frac{\rho v_s^2 g_s}{2}$$

$$\frac{1}{Re} = 1.8 \log_{10} \left( \frac{Re}{6.9} \right)$$

(7)

$$Re = \frac{v_s r_w \rho \dot{g}}{\eta_g}$$

(8)

where $\rho_g$ and $\eta_g$ are the gas density and viscosity evaluated at the surface temperature $T_s$. $Re$ is the cutting gas Reynolds number.

The power, mass and impulse balances are coupled, not only within one segment, but also in consecutive segments. An iterative solution technique by computer results in predictions for the cut kerf shape and the maximum processing speed. Results for homogeneous metals have been proved to be qualitatively correct. The relative error is less than 10%, compared with experimental results [5].

$$3. \text{Synthetic layer damage}$$

For laminated materials the thermophysical and optical properties of the synthetic materials should be inserted in the model. It is assumed that the forces on the synthetic melt layer induced by vapor pressure and surface tension are small compared to the force exerted by the gas jet. These effects are therefore not included in the calculations for laminates. We will also assume that the synthetic material absorbs all incident laser power, regardless of the angle of incidence. The results of these calculations (Fig. 3) are qualitatively correct for the metallic layers, but underestimated for synthetic layers [2]. Apparently, the primary interaction between laser light and synthetic material was not sufficient to explain the measured synthetic layer damage. Now we will pose two hypotheses about the physical background of the synthetic layer damage in order to include a more appropriate physical mechanism in the model:

Hypothesis 1. Heat is conducted via the metal layers to the synthetic layers, causing the synthetic material to melt or degenerate.
Hypothesis 2. Laser power is reflected several times between metallic surfaces, thereby traveling in the direction of the synthetic material.

In the following subsections, the above-mentioned hypotheses will be theoretically investigated and experimentally evaluated. For the purpose of experimental evaluation we applied a Rofin Sinar 1700RF CO$_2$ laser, together with an XY-table capable of velocities up to 0.3 m/s. The laser beam was focused on the workpiece surface by a 4 in. ZnSe lens.

3.1. Hypothesis 1: conduction via metal layers

For a sufficient heat flux into the synthetic layers to heat it up to melting, it is a necessary condition that the temperature in the subsequent metal layers exceeds the synthetic material melting temperature. A suitable expression for the temperature inside the metal layers is given by the solution for a moving cylinder with constant boundary temperature [4,6], described in cylindrical co-ordinates $r$ and $\phi$

$$T(r, \phi) = T_a + (T_m - T_a) \exp(-\rho \cos \phi) \times \left[ \frac{I_0(\rho_0)}{K_0(\rho_0)} K_0(\rho) + 2 \sum_{n=1}^{\infty} \frac{I_n(\rho_0)}{K_n(\rho_0)} K_n(\rho) \cos(n\phi) \right]$$

where $T_a$ and $T_m$ are the ambient and melting temperature of the metal, respectively. $\rho_0=r_0/2\kappa$ is the dimensionless cylinder radius $r_0$ and $\rho=rv/2\kappa$ the dimensionless radial co-ordinate. $I_n$ and $K_n$ are the modified Bessel functions. Now we should consider the maximal penetration depth of the isotherm which represents the melting temperature of the synthetic material.

To evaluate this theory, we considered a laminate made from two aluminum sheets, filled with a polypropylene core. The melting temperature of the aluminum is 933 K, that of the polypropylene is 433 K. The experimentally found cut kerf radius is 150 μm, so the cylinder radius is chosen as 150 μm. With an ambient temperature of 293 K, the maximal penetration depth of the synthetic melting temperature follows from Eq. (9) to be a function of the workpiece velocity (Fig. 4). As can be seen in this figure, the isotherm penetration depth has a typical $1/\sqrt{v}$ behavior. The experimentally found synthetic layer damage is also shown in this figure. The error bars indicate one standard deviation. These experiments were performed at 1700 W laser power. It can be clearly seen in this figure that there is a definite relation between the processing speed and the synthetic layer damage extent. However, this theory overestimates the damage extent by 20% for normal operation velocities. This is due to the assumption that the supply of heat through the metal layers is infinite, which is not true. By heating the synthetic layers, heat is subtracted from the metal layers.

Fig. 3. Experiment and simulation of an Al–PP–Al laminate.

Fig. 4. Penetration depth of synthetic melting isotherm and experimentally found synthetic layer damage.
3.2. Hypothesis 2: multiple reflections

Consider a laminated material, made from two aluminum sheets, separated by a synthetic material of thickness \( d \). It is assumed that synthetic material is affected above a certain power density threshold. Now a laser beam of power density level \( I_0 \) is aimed at an inclination \( \theta \) at the laminate (Fig. 5a). On a small area \( a = d \tan \theta \) of the lower aluminum sheet, the laser beam is reflected with reflection coefficient \( R \). At distance \( x \) from the cut edge, the laser beam is reflected \( x/a \) times, which results in a power law for the average power density \( I(x) \) at distance \( x \) from the cut edge

\[
I(x) = I_0 R^{x/a}
\]  

(10)

The reflection coefficient \( R \) plays an important role in Eq. (10). At the very small inclination angles practically encountered in laser cutting, its value is independent from inclination angle and laser beam polarization, but strongly dependent on the material temperature. For aluminum, \( R=0.962 \) at melting temperature. From Eq. (10) it follows the power density level is halved after \( 18 \) reflections. At room temperature \( R=0.984 \), which means that \( 43 \) reflections are needed to halve the power density level.

It is not possible to quantify a synthetic layer damage extent from this theory, because the power density threshold for damage initiation is not known. However, from the structure of Eq. (10), a large influence of the angle of incidence \( \theta \) is recognized, which gives rise to an evaluation of this theory based on oblique cutting. Cutting experiments are performed on samples that are tilted between 0 and 7°. The applied laser power was 1700 W and the workpiece velocity was 150 mm/s. The results (Fig. 5b) on the lower side of the cut kerf are indicated by a ‘+’, those on the upper side by an ‘o’. Based on Eq. (10), the damage on the lower side should be more pronounced than on the upper side, and the results should diverge for larger angles. However, there is not a clear indication that one side is more damaged than the other, because the ‘most damaged side’ is equally distributed between both sides. As the result of this experimental evaluation, we reject this hypothesis.

4. Discussion

From CO2 laser cutting experiments for laminated materials it is concluded that laser cutting can be applied very well, although a slight damage has to be accepted in the synthetic layers. Also some dross attachment will occur. Clearly, our goal is to minimize the extent of the damaged zone in the synthetic layers. Application of the current laser cutting model, developed for homogeneous metals, on laminated materials shows that for aluminum layers the simulation results are quite good. However, for the synthetic layers the damaged zone extent is underestimated. Primary interaction between laser light and synthetic materials is not dominant in the damage extent of the synthetic layers. From the hypotheses that describe synthetic layer damage, heat input into the synthetic layers via the metal layers is most likely to be dominant. However, more research has to be performed to validate this theory. For instance, experiments with a high-power Nd:YAG laser should not influence the results, because wavelength does not play a role in this theory. A finite element analysis might provide some more detail in this theory, because the current theory is based on an unlimited heat supply through the metal layers, which is not
a correct assumption. Heat is subtracted from the metal layers by heating the synthetic layers.

If the metal layer conduction theory is the dominant mechanism in the synthetic layer damage, then this implies two things: First, the recipe to minimize the synthetic layer damage is simply to cut as fast as possible. The laser cutting model described in this paper can be used to obtain this maximum cutting speed, which is computed as 160 mm/s for the Al–PP–Al laminate considered in the experiments. From this maximum cutting speed, combined with the resulting kerf width, the synthetic layer damage extent is estimated to be 0.6 mm. Taking the model error of 20% into account, the estimate is about 0.5 mm, which is experimentally found. Second, a zero synthetic layer damage extent is not possible, because there will always be some thermal load on the base material.

Other interesting features of the current laser cutting model are numerical optimization and sensitivity analysis. A sensitivity analysis is particularly useful, since small deviations from the nominal processing conditions can spoil the results, especially at maximum speed. For instance, thermal lensing has always been a disturbing factor in the determination of stable process conditions [7]. The results obtained from the sensitivity analysis, used in a computer aided optimization of process conditions, will be applied to construct robust process windows.

Acknowledgements

We wish to thank Dr. D. Petring for the useful information and conversations on modeling of the laser cutting process.

References