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High-speed laser cutting of superposed thermoplastic films: thermal modeling and process characterization

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Abstract

Common thermoplastic films used in the packaging industry have a thickness lower than 100 μm, and present low absorption to CO_2 laser radiation. This characteristic renders the use of cutting parameters, predicted by models developed for thicker thermoplastics inappropriate. In addition, the usual procedures involve the use of an assisting gas, responsible for removing the melted material, which, when processing thin films, induces changes in position in the material. A new theoretical model describing the temperature distribution on thin thermoplastic material during laser cutting was later developed. The heat conduction was solved analytically by the Green function method and heating and cooling thermal stress evolution was taken into consideration. The laser beam diameter over the samples provides the possibility of obtaining two cut operations: a simple cut, on beam focus, and a cut with welding, defocusing the beam. Engineering parameters predicted by the model were applied to cutting superposed high- and low-density polyethylene and polypropylene samples, transparent and white, with thicknesses between 10 and 100 μm, and experimentally validated.

Proper modeling and the introduction of a reflective substrate under the samples allowed the improvement of process efficiency and the achievement of cutting operations up to $20\,\mathrm{m\,s^{-1}}$, and cut with welding up to $14\,\mathrm{m\,s^{-1}}$; an order of magnitude of improvement on industrial

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speeds previously attained for this operation.

Keywords: Lasers; Cutting; Thermoplastic films; Modeling

1. Introduction

The application of laser technology to cutting plastics was one of the earlier uses of that versatile tool. In fact, accordingly to Duley [1], the first published studies date from 1969 when Lunau et al. [2] reported cutting perspex by using CO_2 laser radiation. Since then the technology has shown increasing development. In 1986, Powell et al. [3] referred to the possibility of laser cutting low-density (LD) polyethylene (PE) and polypropylene (PP) thermoplastics with about 3 mm thickness at a processing speed of 2.2 m min^{-1} and 3.4 m min^{-1}, respectively, using 400 W laser power. Four years later, Powel [4] and Chryssolouris [5] both report cutting PE with a thickness of a few millimetres and processing speeds of tens of m min^{-1}. Since then, further developments have been made, not only on increasing the cutting speed [6] but also on new applications [7]. The demand for consumer goods such as food and medical products, packaged in plastic material in a way that quality and hygiene can be preserved, has opened new areas in the laser application field.

The replacement of traditional tools by laser tools can be justified by the increase in the process reproducibility, the simplification of the processing moving parts (no need for "stop and start" production lines) and productivity increase (the laser beam can scan the material faster than mechanical parts). In addition, being a non-contact and non-contaminant process allowed laser radiation to be, from the start, the object of study by the thermoplastic industry. In this area, there is particular interest in cutting superposed thermoplastic films, which represent the main product for the packaging industry.

Although laser UV radiation can be used to cut some types of plastics by photodissociation mechanisms [8], in the majority of cases 10.6 μm laser radiation of CO_2 lasers is chosen [3,5,7,9].

Much of the reported work considers the existence of total absorption by, at least, one of the parts. However, most of thermoplastics used in the packaging industry, like HD and LD PE and PP, with a thickness lower than 100 μm, have low absorption to laser radiation, typically lower than 20%, presenting in most of the cases attenuation length, defined as the inverse of the absorption coefficient, a_T, higher than their thickness, as shown by Coelho et al. [10].

In this paper, a model is applied which allows us to obtain cutting parameters of superposed transparent HD and LD PE, PP and white HD PE samples, all with thickness, h, lower than 100 μm (Table 1 shows the relevant physical parameters of the thermoplastics considered), in a situation without a total absorbing part and no gas jet acting coaxially with the laser beam. Attention is given to the achievement of

Table 1
Thermoplastics parameters for $\lambda = 10.6\,\mu m$

	HD PE		LD PE	PP
	Transparent	White	Transparent	Transparent
Absorption coefficient, a_T ($\times 10^3\,m^{-1}$)[a]	0.822	1.561	1.092	3.831
Attenuation length, L ($\times 10^{-3}$ m)[a]	1.22	0.64	0.92	0.26
Complex refractive index[a]	$1.5–7\times10^{-4}i$	$1.5–10^{-3}i$	$1.6–9\times10^{-4}i$	$1.5–3\times10^{-3}i$
Thermal expansion coefficient, α ($\times 10^{-4}\,K^{-1}$)[b]	3.6	—	4.5	0.8
Thermal conductivity, K ($W\,m^{-1}\,K^{-1}$)[b]	0.490	—	0.335	0.150
Density, ρ ($kg\,m^{-3}$)[b]	952	—	917	890
Specific heat capacity, C_p ($J\,kg^{-1}\,K^{-1}$)[b]	3150	2737	1157	1469
Tensile modulus, E ($\times 10^6$ Pa)[b]	0.80	—	0.25	1.35
Thermal diffusivity, k ($\times 10^{-6}\,m^2\,s^{-1}$)[b]	0.16	0.19	0.32	0.12
Melting temperature, T_f (K)[a]	396	—	377	433
Welding temperature, T_s (K)[b]	474	—	474	500
Dissociation temperature, T_d (K)[b]	583	—	583	598
Latent heat of fusion, L_f ($J\,kg^{-1}$)[b]	103,340	91,685	34,120	47,005
Latent heat of dissociation, L_d ($J\,kg^{-1}$)[b]	2,092,500	—	—	—

[a] Measured.
[b] From Refs. [28–32].

a cut with welding of the superposed parts [11]—an important process for manufacturing, as two operations can be accomplished with just one procedure.

2. Modeling

Laser cutting results in localized melting or chemical degradation. The three mechanisms involved in polymer cutting are melt shearing, vaporization and chemical degradation. If all polymeric materials are cut by a combination of these three mechanisms, for each situation, it can be assumed that one of them dominates the process.

Most thermoplastic polymers are cut by the shearing of a localized melt generated by the applied laser beam. The only commonly used polymer that is laser cut by vaporization is transparent polymethyl methacrylate (PMMA, or perspex), and chemical degradation dominates only when UV radiation is applied.

The use of 10.6 μm laser radiation emitted by a CO_2 laser creates a melt zone which is the object of shearing, usually by the action of a gas jet acting coaxially with the laser beam, or the result of internal forces, as considered in this work. Then, it is important to define a model based on the heat transfer that occurs during the process. This involves the solution of the heat conduction equation:

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = k\nabla^2 T + \frac{Q(r)}{\rho C_p}, \qquad (1)$$

where ρ (kg m^{-3}) is the density, C_p (J kg^{-1} K^{-1}) the specific heat at constant temperature, k (m^2 s^{-1}) the thermal diffusivity, $Q(r)$ the heat produced and $\vec{v}$ the velocity vector.

Assuming that the thermoplastic to be cut moves just in one direction (say, XX), then Eq. (1) can take the form

$$\frac{\partial}{\partial t}\{\Delta T(r,t)\} = k\nabla^2\{\Delta T(r,t)\} - v_x\frac{\partial}{\partial x}\{\Delta T(r,t)\} + \frac{1}{\rho C_p}Q(r), \tag{2}$$

where $\Delta T(r,t)$ is the temperature change (to ambient temperature) and r represents the x, y and z coordinates. The heat produced by the material due to the absorption of laser radiation is given by

$$Q(r) = \frac{4a_T P}{\pi(d/2)^2}\exp\left[-\frac{2(x^2+y^2)}{(d/2)^2}\right]\exp(-a_T z), \tag{3}$$

where P (W) represents the average power delivered by the laser, a_T (m^{-1}) the coefficient of attenuation and d (m) the beam diameter on the material.

In the case of thermoplastic films, the medium can be considered as an infinite half space since $h \gg 2k/v_x$ is valid [12] (as it can be seen in Table 1). Then, considering the laser beam propagating in the ZZ direction, the boundary conditions to solve Eq. (2) are

$$\Delta T(x,y,z,t)|_{t=0} = 0, \tag{4}$$

$$\Delta T(x,y,z,t)|_{x,y,z=\pm\infty} = 0, \tag{5}$$

$$\delta T(x,y,z,t)|_{t=0} = 0 \tag{6}$$

with δT the temperature gradient.

Then, using the Green function [13–15], the solution can be written as

$$\Delta T(x,y,z,t) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{0}^{+\infty}\int_{0}^{+\infty} Q(\xi,\eta,\mu,\tau)\, G\left(\frac{x}{\xi},\frac{y}{\eta},\frac{z}{\mu},\frac{t}{\tau}\right) \mathrm{d}\xi\,\mathrm{d}\eta\,\mathrm{d}\mu\,\mathrm{d}\tau. \tag{7}$$

This methodology has the advantage that the Green function is independent of the non-homogeneous terms of the differential equation; then, having determined the Green function, the solution can be obtained by simple integration [16]. Through this method, detailed by Coelho [17], the solution obtained for (2) is

$$\Delta T(x,y,z,t) = \frac{2a_T P}{\pi\rho C_p}\int_0^t \frac{1}{(d/2)^2+8k(t-\tau)}\exp\left\{-\frac{[x-v_x(t-\tau)]^2+y^2}{(d/2)^2+8k(t-\tau)}\right\} \times \exp\{a_T[k(t-\tau)-z]\}\,\mathrm{erfc}\left\{\frac{2a_T k(t-\tau)-z}{\sqrt{4k(t-\tau)}}\right\}\mathrm{d}\tau. \tag{8}$$

However, as previously stated, the thermoplastic films, the subject of this paper, present high transmission to the laser radiation and the heat conduction in the material is reduced due to low thermal conductivity values. So, the influence of z can be disregarded from the solution, except for a term $\exp(-a_T z)$ in considering beam attenuation through the path. Then, the model can become

$$\Delta T(x,y,z,t) = \frac{4a_T P}{\pi\rho C_p}\exp(-a_T z)\int_0^t \frac{1}{(d/2)^2+8k(t-\tau)} \times \exp\left\{-\frac{[x-v_x(t-\tau)]^2+y^2}{(d/2)^2+8k(t-\tau)}\right\}\mathrm{d}\tau. \quad (9)$$

The thermal behaviour while cooling can be predicted by the relation

$$\Delta T(x,y,z,t)|_{t>t_{\text{inter}}} = \Delta T(x,y,z,t) - \Delta T(x,y,z,t-t_{\text{inter}}), \quad (10)$$

where t_{inter} is the interaction time.

In addition, due to the high transparency that thermoplastic films present to 10.6 μm laser radiation, it was considered the introduction of a reflective material under the superposed films—a metallic substrate was considered. This presence can be simulated by considering the existence of another source under the thermoplastics, resulting from reflectance R^* and is expected to improve process efficiency. Then Eq. (9) should be altered accordingly, resulting in

$$\Delta T(x,y,z,t) = \Delta T(x,y,z,t)|_{\bar{w}/\text{subst}} + (1-A)^2 R^* \Delta T(x,y,|z-2h|,t)|_{\bar{w}/\text{subst}} \quad (11)$$

with $\Delta T(x,y,z,t)|_{\bar{w}/\text{subst}}$ the value expected without the substrate, given by Eq. (9) or (10) and A the film's absorptance.

The above relations allow for the prediction of the engineering parameters needed to achieve a determinate temperature that, for welding purposes, is the welding temperature, T_s. It is common methodology to consider the delivered energy density $(E/A_r)_0$ as a useful parameter combining the values of process variables: laser incident power, P_0, displacement velocity, v_x, and laser spot diameter, d, over the material. Then the expression

$$\left(\frac{E}{A_r}\right)_0 = \frac{4P_0}{\pi v_x d} \quad (12)$$

relates all the most important engineering parameters involved in laser processing. However, besides the energy density needed to increase thermoplastics temperature to an appropriate level, it is also necessary to consider the thermal stresses that occur during the interaction since they are the main mechanisms to be involved in the shearing process.

The expression that gives the material's expansion (or compression) ΔL of the linear dimension L of a material with linear thermal expansion coefficient α_L (K^{-1}) subjected to a temperature change ΔT is [18]

$$\Delta L = \alpha_L L \Delta T. \quad (13)$$

This expression is related to an expansion during the heating phase and to compression during cooling. If one considers that temperature distribution is symmetric with respect to its maximum then, as the material cools, opposite compressive forces appear in the YY direction. The intensity of these forces has a direct influence on the kind of cut that can be obtained. Fig. 1 shows a simplified

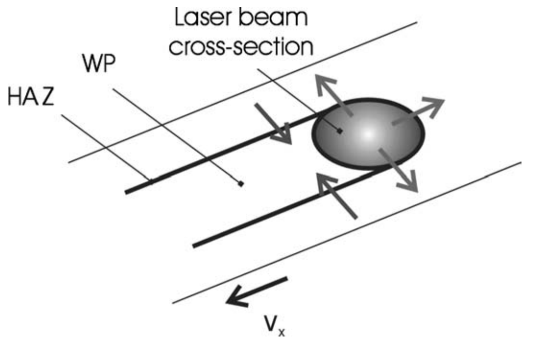

Fig. 1. Simplified schematic representing the action of thermal stresses (arrows) while processing. WP—weld pool; HAZ—heat affected zone.

schematic of this phenomenon. So, in accordance with (13), depending on the beam cross-section diameter over the thermoplastics, it is possible to have different cut characteristics. In order to achieve welding between the two superposed cut plastic films, the laser must have a diameter allowing the proper moisture and distribution of the molten material. This value can be predicted assuming that the beam diameter, d, should be at least of the same magnitude as the film's thickness. Then, from (18) the condition is

$$d > 2h\alpha_L \Delta T \tag{14}$$

with $\Delta T = T_s - T_0$ and T_0 the environment temperature. The stress σ_T (Pa) related to the linear expansion is

$$\sigma_T = \alpha_L E \Delta T, \tag{15}$$

E being the thermoplastic tensile modulus.

3. Experimental procedures

The thermodynamic model defined previously allows the prediction of the engineering parameters necessary to obtain a cut between superposed thermoplastic films with thickness lower than 100 μm. These parameters were applied using a 140–2700 W *Trumpf* CO_2 fast axial flux laser and a rotating drum. A schematic of this last set-up is shown in Fig. 2, where the thermoplastic samples are placed around the drum's curved surface. High linear velocities of up to 20 m s^{-1} were reached by the plastic samples. In this apparatus the focusing lens (with focal length $f = 50$ mm) could change its position with relation to the samples. This focus offset, Δ, allows for obtaining high beam diameters over the samples' surface. Fig. 3 shows the variation of beam diameter over the processing plane, d (m), with focus offset, Δ (m), as measured through a laser beam analyser (LBA 2). At focus, as it can seen on the polynomial equation of Fig. 3, the beam diameter is 0.23 mm.

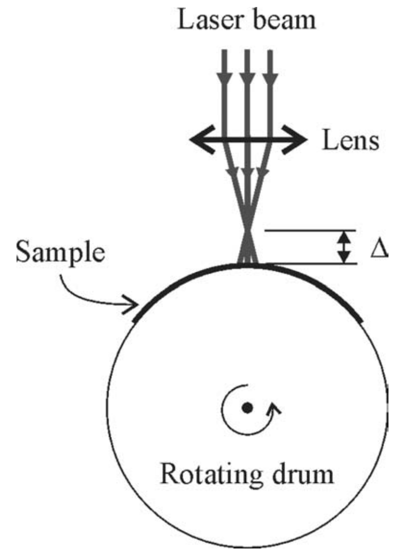

Fig. 2. Schematic of the experimental set-up used for high-velocity welding.

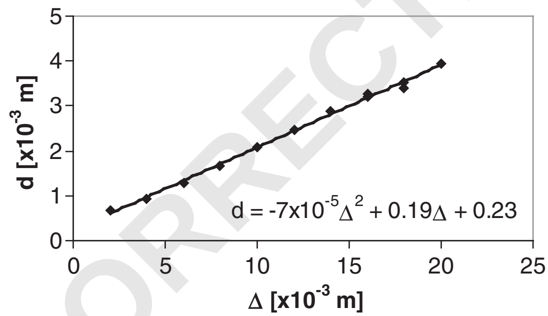

Fig. 3. Beam dimension, d, variation with focus offset, Δ, as measured by a laser beam analyser. The formula presented results from a polynomial fit to experimental data.

The union strength between the resulting two superposed parts was tested to traction. The value of tensile strength, S, for each weld was compared to that of the original thermoplastic and results were plotted as a percentage of the latter. Manufacturing data considered that a "good weld" occurs when $S > 80\%$ [19], as considered by Coelho et al. [20] when analysing the process of high-speed welding of the thermoplastic films.

Underneath the samples, an aluminium substrate was used in order to maximize the process efficiency. Its reflectance was measured to be $R^* = 63\%$ and no significant diffusion was observed on the reflected beam.

4. Fumes

When processing thermoplastics with a laser, attention should be given to the emission in the environment of products resulting from the process. Due to the health risks that can arise, several studies have been published [21–25], allowing a broad knowledge of the materials and fumes emitted. These studies comprehend CO_2 laser radiation and also the thermoplastics considered in this paper.

Fume hazard depends on a number of factors, including material toxicity—determined by the chemical composition of the fume—and the amount of particulate (dust) present that is respirable—known as aerosol. The authors agree to assume that thermoplastics of the polyolefin family, like PE and PP, are those that show higher emission of aerosols (between 140 and $>300\,\mathrm{mg\,m^{-3}}$) and that these particles present diameters between 0.13 and 0.50 μm. Benzene and formaldehyde are, in accordance with Graydon [22], the main carcinogenic products.

In order to comply with the security requirements, a fume exhaustion system (Nederman) and a fume monitoring system (Quantum Inst., Inc.) were used, thus protecting and monitoring the surrounding working area. However, work developed in monitoring the interface area [26,27] has shown that fumes released during the processing are responsible for the absorption of about 30% of the incident energy due to plasma formation in the air above the interaction interface. Therefore, based on these observations, the values of P_0 (or E/A_r) predicted by the model should be affected by a term $(1+\beta)$ in order to be applied in cutting procedures, β being the power loss before reaching the sample surface. In our case this was $\beta=0.3$. Removing any interaction product by applying a gas jet parallel to the surface makes $\beta\sim 0$.

5. Model validation

Applying relation (11) to thermoplastic parameters presented in Table 1, it was possible to predict the engineering parameters necessary to cut the superposed samples. In addition, from condition (14), it is expected that $d>1.2\,\mathrm{mm}$ is the condition necessary to obtain both cut and welding in the same operation. This was confirmed experimentally. Fig. 4 shows an example of the variation on the relative weld strength to traction, S (%), as the beam diameter over the sample, d (mm), increases (transparent HD PE, $h=30\,\mu\mathrm{m}$, $v_x=2\,\mathrm{m\,s^{-1}}$, $E/A_\mathrm{r}=0.5\,\mathrm{J\,mm^{-2}}$). Then, as expected, two situations can be considered: a cut, at beam focus, and a cut with weld when $d>1.2\,\mathrm{mm}$.

Fig. 5 shows the comparison between predicted (lines) and experimental (points) where $(E/A_\mathrm{r})_{0m}$ minimum values are necessary to obtain a cut and a cut with welding for all the thermoplastic films considered. Predicted values have a standard deviation of 12% (not shown in graph) and the presence of a reflective aluminium substrate under the samples is assumed. These values were constant (within their standard deviation) with processing velocity, as can be seen from experimental data obtained

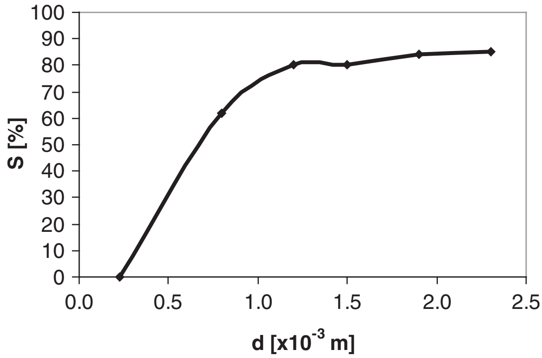

Fig. 4. Measured union strength, S, between separated parts as the laser beam diameter, d, over the sample increases. Example of 2 m s^{-1} processing a 30 μm transparent HD PE, with $E/A_r = 0.5\,\mathrm{J\,mm^{-2}}$.

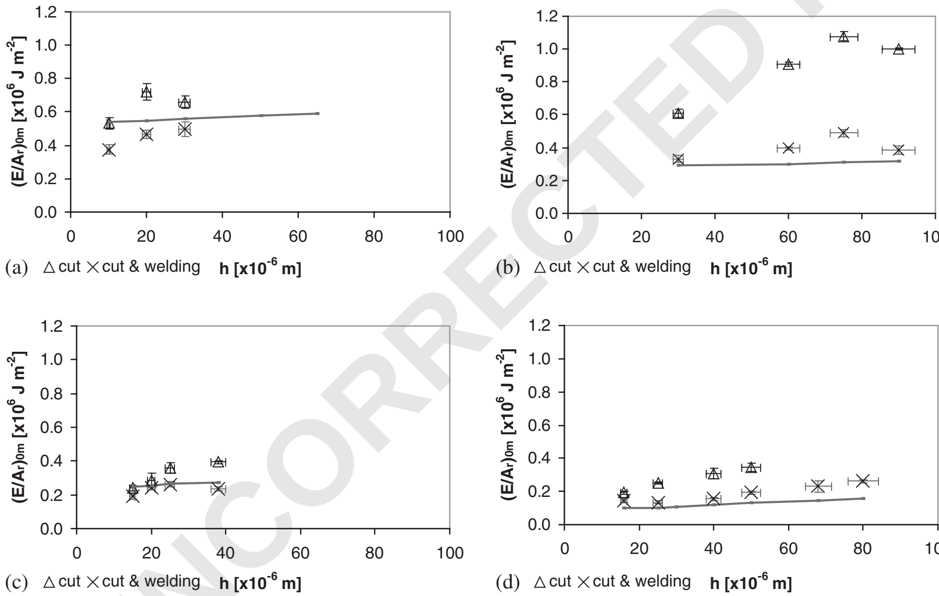

Fig. 5. Comparison between predicted (lines) and experimental (points) cutting and cutting with weld minimum energy density delivered on the samples, $(E/A_r)_{0m}$, for (a) transparent HD and (b) LD PE, (c) PP and (d) white HD PE.

for the cut operation (Fig. 6). Processing speeds up to 20 m s^{-1} were accomplished for this operation, and up to 10 m s^{-1} for a cut with welding.

The graphs presented in Fig. 5 show significant differences between a cut and a cut with welding; while this last operation occurs for $(E/A_r)_{0m}$ values close to those predicted (taking into consideration the dissociation temperature), a cut without

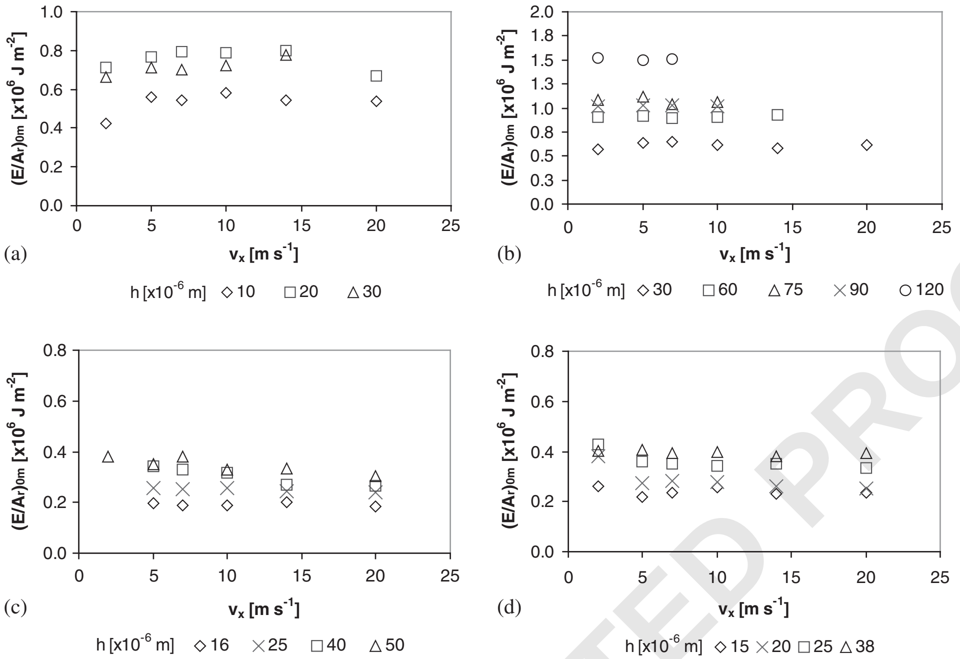

Fig. 6. Experimental cutting minimum energy density delivered on the samples, $(E/A_r)_{0m}$, data variation with processing velocity, v for (a) transparent HD and (b) LD PE, (c) PP and (d) white HD PE.

welding needs about 50% higher values. However, it was observed that dissociation, in fact, starts before these energy density values, but it is not complete—some of the material in the heat affected zone (HAZ) during the cooling phase, partially occupies the volume of dissociated material. This results in the appearance of thin material threads between parts, as can be seen in the photo in Fig. 7.

This fact can be explained on the basis of Fig. 8, where the differences in the sample's temperature in time and space evolution for the two situations can be seen. This example, for the $2\,m\,s^{-1}$ processing of a $30\,\mu m$ transparent HD PE, shows that when a cut without welding is obtained (laser beam focused on the sample), the cooling is reduced and the material does not remain for long at the maximum temperature induced by the laser. In addition, the affected zone is small, the temperature distribution being relatively limited. By contrast, when it is defocused over the samples, not only is the interaction time high but the temperature profile also comprises a broader quantity of material. This allows the welding phenomenon in the interface between the thermoplastic's irradiated and unaffected areas, where the temperature gradually decreases. The time between a 10% and a 90% variation on temperature was determined as being 0.04 s for a cut situation and 0.30 s for a cut with welding.

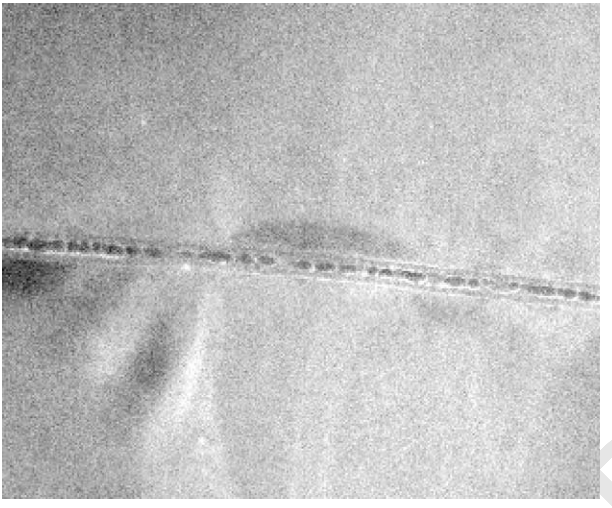

Fig. 7. Example of thin material threads appearing between parts.

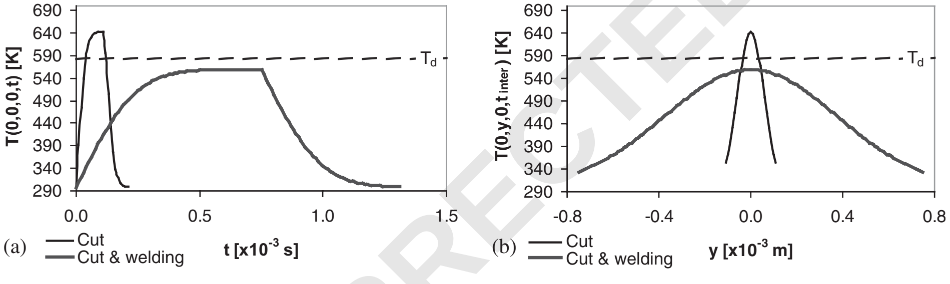

Fig. 8. Calculated values for (a) temperature evolution with time and (b) temperature profile, for cutting a transparent HD PE with $h = 30\,\mu\text{m}$, $v = 2\,\text{m}\,\text{s}^{-1}$, $d = 1.5\,\text{mm}$ (cut and welding) and $d = 0.23\,\text{mm}$ (cut). Maximum error associated to temperature data determination is 12%.

Table 2
Minimum σ_T/E values necessary to the cut operations

HD PE		LD PE		PP	
Cut	Cut and weld	Cut	Cut and weld	Cut	Cut and weld
$d = 0.2\,\text{mm}$	$d = 1.2\,\text{mm}$	$d = 0.2\,\text{mm}$	$d = 1.2\,\text{mm}$	$d = 0.2\,\text{mm}$	$d = 1.2\,\text{mm}$
0.12	0.10	0.29	0.20	0.07	0.04

Table 2 presents the minimum σ_T/E values necessary to achieve each of the two cut operations for the three kinds of thermoplastics considered in this work. These values result from the application of expression (15) to experimental data, and complement the developed model.

6. Conclusions

Cut superposed thermoplastic films, with a thickness lower than 100 μm, were successfully modeled. The Green function method allowed us to obtain the temperature distribution induced in the material by the laser radiation, which, in conjunction with the consideration of related thermal stresses, allowed the prediction of engineering parameters for several transparent HD PE, LD PE and PP, as well as for white HD PE. Two cut operations were characterized: a cut and a cut with welding. The first, obtained at laser beam focus, transformed the two superposed films into four separated parts, and high speed up to $20\,\mathrm{m\,s^{-1}}$ was accomplished with a 2.7 kW CO_2 laser. The welding of the separated parts is achieved when the beam diameter over the samples is higher than about 1.2 mm, a fact predicted by the model, but at lower processing speeds ($<10\,\mathrm{m\,s^{-1}}$).

The model and processing procedures demonstrate that these cut operations can be accomplished without the need of an assisting gas jet, thus minimizing operating costs. The fact that high speed is accomplished and that cut and welding can be obtained in a single operation gives this method a high degree of importance in the plastics industry.

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