IMPROVEMENTS TO LASER PROCESSING OF THIN POLYMER FILMS –USING NON-STANDARD NOVEL LASER WAVELENGTHS

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Abstract

Highly reliable high power carbon dioxide lasers are being increasingly employed in the converting industry. New laser sources with different wavelengths are available to allow more controlled laser cutting and perforating processes. These process advantages are thought to be due to enhanced absorption of certain thermoplastics at these shorter wavelengths and this paper investigates these.

Introduction

Laser cutting has now been widely used for many years and almost all industries have benefited. From a materials standpoint, most engineering materials have been cut – or have been attempted. In this context, laser cutting of thin film plastics is a relatively trivial task, but as is always the case, when this process is incorporated into an industrial environment the challenge is much greater. This is especially true in the case of web processing of thin plastic films due to the very high process speeds that are typically required in the converting industry.

Sealed CO_2 lasers

A major benefit of cutting thin film plastics is that very high process speeds with relatively low average power are possible. Sealed CO_2 lasers delivering up to 500 watts have been widely used for cutting and perforating thin polymer films for some time in the converting industry.

Over the past 15 years, RF-excited, sealed CO_2 sources delivering between 25 and 500 W average power have become available for a diverse range of applications in light manufacturing to the point where unit sales of these lasers now far exceed those of higher power. This reflects the updating of light manufacturing production processes. Compared with more powerful gas and solid-state sources, sealed CO_2 lasers offer advantages to a wide range of applications in engraving, marking, cutting and rapid prototyping markets [1]. This diversity of applications leads to a variety of requirements that, in some cases, could potentially create a large number of lasers. However, two resonator technologies, waveguide and slab construction, are becoming the leading platforms for industrial applications. These two laser architectures have been commercially available for some time, and have continued to evolve. These lasers can provide operating lifetimes in excess of 20,000 hours with minimal maintenance.

The output power of the design scales with the area of the electrodes, allowing slab lasers to maintain cost effectiveness up to 500W. The addition of water-cooling to these designs enables production of high peak and average power for the long durations that are required by many industrial processes.

Recently, new CO_2 laser products have become available with significant flexibility in selecting the actual emission wavelength of the laser. The ability to select different wavelengths can be achieved in two ways: firstly, using wavelength selective optics and secondly; using a unique patented technology that uses common isotopes of the CO_2 molecule [2]. Although the details of these approaches is not relevant to this paper, a number of emission wavelengths from 9 μm to 11 μm are now commercially available with the average power required by industry. Lasers operating at 9.4 μm have been developed because of the high absorption of polyimide (Kapton) polymers at this wavelength [3]. The particular wavelength under consideration here is 10.2 μm. The specification of these lasers is 10.23 +/- .05 μm, lasers run typically at the lower end of this specification. There is experiential evidence that at 10.2 μm wavelength, some thermoplastic films are more efficiently processed than at the longer 10.6 μm wavelength.

Digital Converting for Labels

Laser cutting and drilling processes require very highly focused lasers beams that generate power densities at the workpiece of > 10^6 W/cm^2. In this regime, instantaneous vaporization and high speed cutting of thermoplastic films is possible. Digital converting of labels is an example of an industrial cutting process based on CO_2 laser technology. Digital converting is having a direct impact on the label industry, especially as roll fed digital printing systems gain market acceptance. Laser digital converting allows label producers to make instantaneous job order changes and pattern modifications without the need for tooling - label shapes may be instantly changed and any programmable shape is possible. This enables product enhancements such as personalization. The flexibility of the laser allows automatic adjustment for micro-perforation, through-cut, kiss-cut and scoring at one laser digital converting station. Most importantly, the productivity of a roll fed digital

printing system is dramatically increased. Assuming the label substrate remains the same, the label producer can now run multiple jobs on the same roll and leave the web intact. This can greatly reduce the current delays experienced on a digital press when the label is mechanically die cut. Material is through cut by adjusting the cutting speed to allow the beam to fully penetrate the material. Kiss cutting to a liner is accomplished by increasing the cutting speed or reducing the laser power for a given material. If the material is a Pressure Sensitive Adhesive (PSA) with a silicone liner, it is possible to score the PSA to the liner, but not break through. Utilizing this technique, fold lines, and other material weakening characteristics can be accomplished.

Another attribute of digital laser converting is the ability to rapidly pulse the beam on and off at 2500 Hz or greater. This allows a digital converting system to feature micro-perforate or zone micro-perforate roll or sheet-fed materials at high production rates. By controlling the laser on and off time the length of the perforation and the land between perforations can be varied. The non-contact nature of a laser perforation means that it is highly consistent and is not subject to problems associated with mechanical die wear. This flexibility offered by digital converting therefore allows the digital printer to increase their in-house efficiencies. Due to the initial high capital cost of digital printing system it is important that productivity is high. Figure 5 shows an industrial application of high speed laser-based thin film converting.

Thermoplastic Packaging films

Polypropylene films are widely used in all areas of the packaging industry and hence this is a key material for study. Films are made in a wide variety of single and multi-layer forms, printed or otherwise. No single process is used to make plastics packaging materials. Instead packaging forms the most important market for several plastics processes especially film extrusion, sheet extrusion and blow molding. Indeed packaging is significantly the largest end use market for thermoplastics, estimated at ~16 million tones pa, this despite the widespread progress of polymer and process technologies directed at the reduction of film thickness ("down-gauging") and package weights generally. Plastics packaging can be classified into several groups:

- Primary packaging of the finished product, in the form of bags, pouches, bottles or other containers.
- Secondary packaging for the primary packaged product in the form of shrink or stretch films, bottle crates and transit containers.
- Retail packaging in supermarkets and other outlets, in the form of bags on the reel, wicketed bags, check out bags and shoppers.
- Consumer packaging, in the form of freezer bags and cling-films.

Flexible packaging films are rapidly changing how perishable food products are delivered to the marketplace. Barrier properties required of these films typically consist of multi-layers that commonly include homopolymer or copolymer polypropylene, polyethylene and EVOH barrier layers. As an example of a recent innovation, laser scoring is now an accepted method to form lines of weakness in the film for easy-opening by consumers.

Laser processing performance of thermoplastic films can be defined by the amount of laser energy that is absorbed in the film - the greater the absorption, the more efficient the laser process in terms of higher production rates and lower film damage. Improved understanding of the absorption processes should transfer into improved cut speeds and process control. However, converters have noted that there are distinct differences in the laser processing performance of polypropylene when the shorter wavelength 10.2 μm CO_2 laser is used. This work therefore aims to verify and quantify effects experimentally and to investigate the theoretical background.

The problems of using lasers to process thermoplastics was highlighted by the lack of success in laser welding thermoplastic films. Although this would appear to be a trivial task because of the low melting pint of the polymers, variations in absorption from batch-to-batch of the same plastic (caused by changes in crystallinity) is blamed for the difficulty [4]. An alternative approach that avoids these absorption problems entirely has been presented recently [5]. This work demonstrated Proof of Principle using a novel laser line source to weld typical LDPE, PP and even PLA thin films.

Infra-red Spectroscopy of Polypropylene

To improve our understanding, it was necessary to research the relevant spectroscopy data. The technique of IR Spectroscopy is widely used to characterize materials and fortunately there is a wealth of data available on common thermoplastics, especially on polypropylene [6]. However, before we can interpret this spectroscopic information, some explanation is required.

Organic functional groups differ from one another both in the strength of the chemical bond(s) involved, and in the masses of the atoms involved. For example, we know from the different vibrational characteristics of the bonds that the O-H and C=O groups will absorb IR radiation at different positions in the electromagnetic spectrum. The presence of a strong, broad band between 3200 and 3400 cm^{-1} wave number (wave number in cm^{-1} is simply the inverse of λ, wavelength) indicates the presence of an O-H group in

the molecule, while the presence of a strong band around 1700 cm^{-1} confirms the presence of a C=O group.

For organic molecules, the infrared spectrum can be divided into three regions. Absorptions between 4000 and 1300 cm^{-1} wave number are primarily due to specific functional groups and bond types. Those between 1300 and 909 cm^{-1}, the fingerprint region, are primarily due to more complex interactions in the molecules.

There is a clear absorption band in the center of this fingerprint region at 973 cm^{-1} (10.28 μm) that coincides very closely to the specific laser wavelength under study here, 10.2 μm, figure 3 [7]. This band is known to correspond to a vibrational mode in polypropylene. As polypropylene is a semi-crystalline polymer, these vibrational modes can be complicated by coupling and are not simply due to the motion of one functional group. The band at ~ 973 cm^{-1} is predominantly due to C-C stretching modes and a methyl (CH_3 or Me) twisting vibration, i.e. characteristic of the polymer chain axis [8]. Due to its semi crystalline nature, the vibrational spectra of solid and molten polypropylene are very different. There are a number of vibrational bands called "regularity bands" which are characteristic of ordered or regular sequences of the polymer helix, normally incorporated in the crystalline lattice. The 973 and 998 cm^{-1} pair, figure 3 are both regularity bands, and indeed the relationship between their intensities has been used to calculate the crystallinity (amount of crystalline polymer), since the 973 cm^{-1} band is also partly characteristic of disordered regions of the sample with an irregular conformation. Also, the 998 cm^{-1} band is characteristic of longer sequence lengths (> 11 or 12 C) and the 973 cm^{-1} of shorter sequences (> 5 C).

To summarize, the branched out-of-plane bending introduced into the ethylenic system to produce polypropylene may possibly be responsible for the observed improved laser processing at the 10.2 μm wavelength. The fact that FTIR Spectroscopy data on polyethylene shows no such absorption peaks supports this suggestion.

Experimental Work

Laser cutting is intrinsically a very dynamic process in which material properties are changing very rapidly and hence room temperature data can be misleading. Industrially relevant film materials are therefore used here in an appropriate laser processing regime to identify effects in a semi-empirical manner.

The challenge of optimizing the laser cutting process is usually to identify the maximum cut speed for a particular average power that gives the required cut quality. In this case we need to:

(a) quantify cutting speeds for laser cutting of thin film polypropylene

(b) compare cutting speeds of these films between 10.2 and 10.6 μm lasers

Equipment and Set-up

Two CO_2 lasers, one emitting at 10.2 microns and the second emitting at 10.6 microns, figures 1 and 2, were each set up in turn with a common set of beam delivery optics. A X3 beam expander was used in the optical path before the standard 2.5" focus lens. This enables a small laser spot to be produced at the workpiece. For static absorption trials, a very low average power. 1.3 W, and very low power density is needed to avoid melting and destroying the thin films, therefore the target films were positioned well below the focal point of the beam. Five results were taken for each data point and averaged.

The thin 50 μm polypropylene film studied is a very widely used packaging material, Biaxially Oriented PolyPropylene (BOPP). This isotactic material has been thermally extruded from a homopolymer, molecular weight ~ 1.9×10^5. These BOPP films are widely used in the packaging industry because of their very desirable range of properties. Recent work on their morphology using Atomic Force Microscopy (9) has collected surface morphological information. It has been shown that these films are characterized by a fibrous network structure on the nanometer scale and this is controlled by the drawing process during the fabrication of the film.

For the cutting trials, laser power was increased to a fixed 33 W at the workpiece with the focal point at the workpiece surface. At this point the power density is 0.42×10^6 W/cm^2. The target films were positioned accurately at the focal point of the 2.5" lens. No gas assist was used; all that is required is a flow of clean air to stop deposition of fumes onto the focusing lens. At this power density, cutting speeds for thin polymer films are high. Films were lightly bonded to a variable-speed rotating drum. Both lasers were run at close to continuous wave (CW) and a single pulse of 120 ms was used. At this pulse length, a satisfactory length of cut was produced over the full range of rotational speeds employed. Maximum cut speed was determined by increasing speed in an incremental manner for each material thickness until perforation rather than complete through cutting was obtained. Polypropylene films of 50, 100 & 180 μm sheet thicknesses were laser cut to generate a speed v thickness relationship. It is important to note that the thicker films were not oriented films. Appropriate increments of cut speed were used to produce an abbreviated experimental matrix.

Cut quality is very difficult to quantify on thin film materials, with most of the detail invisible to the naked eye and hence not of primary concern in this work. However, during testing, a semi-quantitative cut quality assessment was made on the basis of full penetration, kerf

width, cut taper and degree of melting. Average power was checked at the start of each series of trials using Coherent Labmaster power meters.

Data reported here uses 'T' to denote that the major orientation of the polymer film is transverse to the cutting direction. Conversely, 'P' identifies results that are taken with the cutting direction parallel to the major orientation of the film, the machine-draw, and hence also parallel to the direction of motion of the web.

Results and Discussion

Static absorption results for single thicknesses of film were tabulated, table 1. These results show that absorption is very much higher for the shorter 10.2 μm wavelength laser on the BOPP oriented film. It is of real significance that the absorption of the 50 μm BOPP film is highly dependant on the orientation of the film, the thicker less highly oriented films do not show the same effect. This result does not appear to apply at 10.6 μm. This suggests therefore that the orientation process itself has a significant effect for thin films using a 10.2 μm beam. For the thicker non-oriented films, the absorption increases with sample thickness as would be expected from theory. At 10.6 μm, absorption starts low and increases again in accordance with theory, but does not increase to the same level as with 10.2 μm. The general trend of the laser cutting results presented in Figure 4 agrees with these static absorption results. A large increase in cut speed at the 50 μm thickness can be confirmed for the 10.2 μm wavelength. And again this is highly dependant on film orientation. The end result is an increase of almost a factor of 3 in cut speed for these oriented films.

In this special case of laser thermal or vaporization cutting, with no co-axial assist gas, the absorbed laser energy heats and transforms the cut kerf volume into a vapor with only limited melting and edge damage. The thermal conductivity of these non-electrically conductive polymer films is typically very low, hence very little energy is lost by conduction assuming optimum cutting conditions. Also, as in all laser cutting processes, total absorption is rare and in this special case, the reflectivity of plastics materials is low at these infra-red wavelengths. Hence, it is likely that absorption of the laser beam plays a critical role in the cutting process.

Figure 3 suggests that the structure of the polypropylene molecule itself causes the improved absorption of the shorter 10.2 μm laser beam but the reasons behind the important dependency on polymer orientation is less clear. There are two possible explanations for this that require further investigation:

(a) the polarization state of the incident laser beams

(b) the relative amounts of draw in the BOPP films

One question raised by this data is why cut speeds for the thicker materials are not significantly higher at 10.2 μm than at 10.6 μm? This could be due to minor differences in the optical characteristics of the two laser beams.

It should be noted that there are two major techniques for manufacturing BOPP films. These produce different orientations, known respectively as machine-draw in the longditudinal direction and transverse-draw. The Stenter technique involves a separate transverse-draw process whereas the 'Bubble' technique employs a blowing process to orient the film equally in the transverse direction and hence produces a more balanced draw. Further work is therefore required with films that have known draw ratios to isolate the effect of the degree of orientation on the cutting process.

Conclusions

1. Very significant effects associated with using a novel laser wavelength within the far infra red regime to cut thermoplastics have been observed and quantified
2. Laser cutting speeds for thin polypropylene films were much higher using a shorter 10.2 μm wavelength than the typical 10.6 μm wavelength.
3. Very marked cut speed differences were observed that depended on the orientation of the BOPP film.
4. A possible explanation for the higher laser cutting speeds is based on the molecular structure of polypropylene.
5. In certain instances it may now be possible to choose the laser emission wavelength that corresponds to the specific infra-red bond resonances of the target layer in a multi-layer polymer film material.

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Figure 1 < 100 w 10.6 µm CO_2 lasers

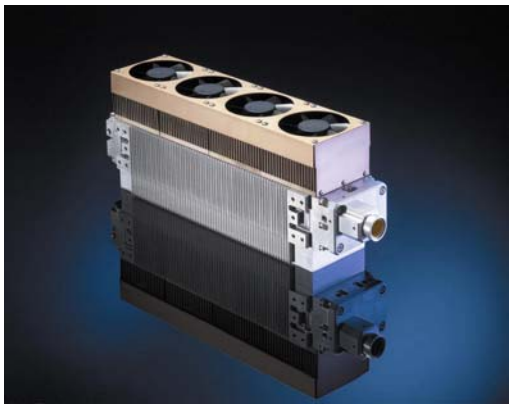

Figure 2 40 watt 10.2 µm laser

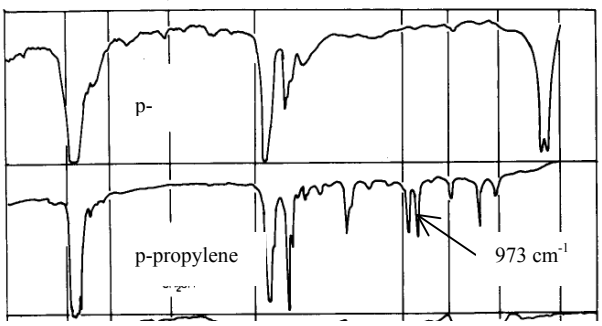

Figure 3 Ordinate is 100% transmission

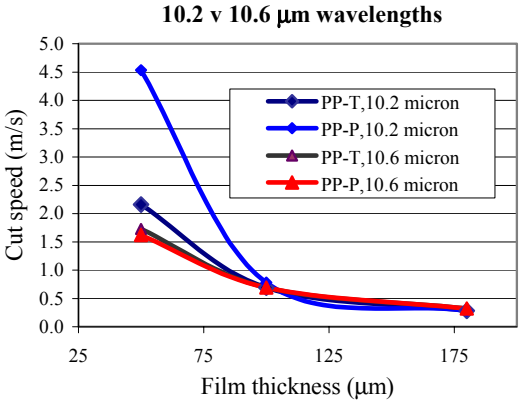

Figure 4 Effect of wavelength on cutting speed

λ=10.25 µm	**Orientation**	
Thickness (µm)	P	T
50 (BOPP)	58.6	83.7
100	18.5	18.5
180	92.4	92.4
λ=10.6 µm		
50 (BOPP)	7.0	14.7
100	28.5	28.5
180	46.2	46.2

Table 1 showing static absorption results in %

Figure 5 shows an industrial converting application