Laser Welding of Polymer Micro-Fluidic Devices using novel Diode Laser Sources

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The most widely used basic building block for high power diode lasers systems is a 19 emitter diode laser bar. For materials processing tasks, these may be used as single bars, can be built into vertical stacks or may be fiber coupled. For certain applications a line of light is preferred to a round beam and hence the use of fiber optic delivery may not be necessary. Straightforward optics can be used to convert the divergent output from this diode bar into a rectangle or line of focused light but the uniformity of the beam within this rectangle is a major problem. When diode bars are stacked vertically, this problem becomes 2 dimensional for anything other than a tightly focused beam. In particular, when a single bar line source is used to cover a large surface area by motion normal to the long axis of the beam, this non-uniformity creates fluctuations in intensity due to the separation between the individual emitters on the bar. This in turn causes processing problems when a laser line is used to seal multiple micro-fluidic devices. This work reports the use of a novel technique combined with conventional fiber delivered sources and novel laser line sources to tackle this problem.

Keywords: high-power, laser, direct, diodes, welding, joining, plastics, micro-fluidic.

1 Introduction

The major application of high average power laser diodes outside the telecom industry is for pumping of a range of alternative laser media such as Nd:YAG and NdYVO₃. Diode lasers are also stimulating important developments in the Reprographics industry followed by others in medical, military, scientific and microelectronics areas. This progress has been enabled by significant increases in diode laser lifetimes, due in part to the increased use of aluminum-free high power laser diodes. Diode laser joining of plastics is now following in industrial acceptance. In parallel, a number of novel joining processes are being developed that take diode lasers in some very novel directions [1].

2 Laser Welding of Plastics

Laser welding of plastics has been investigated by a number of researchers, early work was performed by Duley [2] using far infra-red CO₂ lasers. It was shown that at this wavelength most polymeric materials absorb strongly and that deep penetration 'keyhole' welding might be carried out. Results were mixed with some very high process speeds being reported but joint quality and consistency was unclear. Nonhof [3] used flashlamp pumped solid state Nd:YAG lasers emitting at 1.06 μm to join plastics and showed that due to the thermal properties of plastics, keyhole welding is limited to a small number of materials with a boiling point. Nonhof also pointed out that at that time the most common mechanism for heating plastics is via surface absorption. A 1987 US patent [4] identifies the transmission welding technique, where this surface effect is used to produce a joint between transmitting and absorbing layers of plastic. The development of this process has been facilitated by the availability of highly reliable, easy to use, controllable diode laser systems but the major limitation of the process is the requirement for adequate transmission of the laser beam through the upper layer of the joint and it has also been shown to be possible to produce large area welds at average powers up to 200 watts [5].

2.1 Micro Welding of Plastics

Making very small joints with minimal heat input is of importance in some industries to avoid degradation of the mechanical properties of the joint area. In particular, joining of small diameter tubes is of commercial interest to the medical industry. Although a number of material types are used for tubing in the medical industry, the Teflon® FEP (Fluorinated Ethylene Propylene) range of materials are sometimes employed because of their excellent chemical resistance. In addition, their melt-processible nature allows them to be extruded into tubes. They are however, still considered relatively difficult materials to join and are considered to be a challenging application for the transmission welding technique. Nevertheless, recent results reported in [6] shows how these difficult tube materials can be welded and how the welding process can be scaled down in power and feature size to demonstrate the controllability
of the process. Recent work has led to a limited introduction of this transmission welding technique into industry. It has been shown that a number of engineering plastics materials transmit adequate laser power such that these materials may also be transmission laser weldable [7].

3 Transmission Welding of thin Polymer Films

![Lap welded 2x 150 µm polycarbonate film.](image)

Laser transmission welding of thin film materials has not to date not been addressed using diode lasers apart from in [8] and further developments are reported in this work. Most thin, unfilled non-colored polymer films will transmit a high percentage of incident infra-red laser light under certain laser conditions. These low irradiance and relatively low power (<100 watts) conditions are also those currently provided by commercially available diode lasers. The novel technique proposed here relies on an IR absorbing backplate, tentatively referred to as Reverse Conduction Welding (RCW), to absorb and re-transmit heat transmitted through, in this case, clear polycarbonate films, figure 2.

![Reverse Conduction Welding schematic](image)

Equation 1

\[ I = I_0 e^{-\alpha t} \]

where \( \alpha \) = absorption depth (cm\(^{-1}\))
\( I \) = intensity (MW/cm\(^2\))
\( t \) = thickness (mm)

Figures 1 & 2 show that both polycarbonate and acrylic materials transmit a very high proportion of the diode laser beam, even at much greater thickness than are used in micro-fluidic devices. It is also shown that using both the longest and the shortest commercially available diode laser wavelengths has little or no effect on transmission. Extending these trials to colored acrylics (very similar chemically to polycarbonate) shows that as might be predicted, some colors produce greater absorption than others. The power density and average power employed were chosen to represent those parameters likely to be used during the welding process. Under these conditions, without any heat conduction away from these thin films (as occurs in the RCW process), melting would occur rapidly so the data might be extrapolated to the thin films used in this work. Hence figures 1 & 2 show data which is more relevant than more widely available spectroscopic data.

4 Laser Welding and Sealing of Micro-fluidic Devices

With the latest advancements in lithography, microinjection molding, and related technologies, it is now possible to produce moldings in very high volumes with features in the range of microns [9]. A current application for this micro-molding technology is in the medical industry where these devices may be used to help identify unknown substances or determine key DNA codes from a single drop of fluid, such as in µ TAS (micro Total analysis System). The use of thermoplastics for these applications offers significant advantages: the low manufacturing cost of polymers allows the creation of low cost, and in some cases disposable devices. In the biomedical industry, the use of disposable devices eliminates the sterilization risks associated with reusable medical devices [10]. Polycarbonate type materials are prime candidates for two main reasons: firstly, highly sophisticated techniques have been developed for molding high volumes of compact discs, and these are very appropriate for the high volume production of low cost micro-fluidic devices. Sealing of these devices to ensure absolute hermeticity is of great importance and it was thought that the aforementioned technique used for welding of thin polymer films might be appropriate. Hence polycarbonate CD’s that had been produced as a result of molding trials were used to evaluate the possibility of sealing these devices using diode lasers.

Initial exploratory phases of this work involved the determination of whether adequate transmission of the laser beam through appropriate joint materials was possible. This was done using an approximate assessment of the transmission of the specific material based on:

![Transmission data for clear polycarbonate](image)
Effect of wavelength on clear and colored acrylics

![Effect of Wavelength on Clear and Colored Acrylics](image1)

**Figure 4** Effect of color and diode laser wavelength

It is usually very difficult to compare the effect of laser wavelength in a meaningful manner, but the interchangeability of diode laser modules allows laser sources and beams that are entirely identical other than in wavelength to be used giving a very fair comparison, results are given in figure 4.

### 4.1 Experimental set-up

![FAP Diode Laser System](image2)

**Figure 5** FAP diode laser system

Having confirmed adequate transmission for the preferred material for the micro-fluidic sealing application, the next stage was to identify a suitable laser source. Initially, a standard fiber-delivered near infra-red low power industrial laser system emitting in the 810 nm wavelength regime [12] was used to develop laser processing parameters. Towards the end of the experimental program, a prototype laser line source device was also employed, figure 6.

### 4.2 Materials

Laser welding of plastics requires that the materials to be joined are similar chemically so that when controlled melting is produced, mutual wetting occurs across the joint. This does not necessarily require an intermediate absorbing layer if the Reverse Conduction welding technique is employed. Laser welding does however demand a level of material compatibility if a high strength thermal bond is required. Polycarbonate and its derivatives are the materials of choice for these micro-molded devices, hence Bayer Makrofol® polycarbonate films were chosen for sealing. Although it was shown that it was possible to weld films as thin as 6 µm to seal the devices, the samples presented here were all prepared by sealing a 20 µm film onto a 1.2 mm thick polycarbonate molding in the form of a compact disc. The cd format is used simply because cd molding machines have the ability to reproduce very small features and structure on the surface of the cd.

### 4.3 Welding trials

![Schematic of High Brightness Line Source](image3)

**Figure 6** Schematic of high brightness Line Source

Power density requirements were taken from previous work [8].

Using parameters and tooling developed for the RCW technique from previous work [8], a 200 mm focal length lens was used to give a spot size of 4mm. This long focal length gives a very usable depth of focus. This laser spot produced a weld joint slightly larger than 4mm due to conduction effects, although smaller joints were possible if smaller spot diameters were used. An appropriate number of increments of average power and pulse time were used to produce large diameter spot welds between the polycarbonate film and the clear polycarbonate substrate.
During these initial ranging trials, it was noted that excellent part fit up was needed to produce a high quality weld. This was found to be particularly true for welding of thin films due to their rapid distortion and buckling at low power inputs.

These ranging trials also showed that at higher speeds, the tooling was inadequate to maintain flatness at the weld point and hence the usable laser power was limited to 12.6 watts. At laser powers below 3 watts, welding became unstable, hence identifying the process parameter envelope. The same laser powers were employed for both the spot and seam welding. For the line source welding, the process instability associated with the tooling and clamping occurred at an average power of 6 watts. Although the low ripple line source used was capable of up to 40 watts average power in a 19 x .065 mm line, this power capability was not employed. Weld speeds were from 50 mm/min to 100 mm/min.

5 Results

5.1 Spot Welding results

Spot welds were produced between the film and the polycarbonate to identify an approximate value for the energy (W/s) for this material combination.

![Figure 9 Spot welding results with FAP System](image)

![Figure 10 Peel test film failure](image)

![Figure 11 showing 'sucking in' of film](image)
5.2 Seam Welding results

The maximum welding speed at which a consistent welding process was possible was identified. This allowed an abbreviated experimental matrix of trials to be performed spanning a range of average powers, figure 10. No thermal damage was noted but some ‘sucking down’ of the film was noted, figure 11.

Figure 12 Seam welding results with FAP system

Figure 13 FAP welded seam

5.3 Line Source Results

At the highest welding speeds, incomplete thermal joints were noted, with low joint peel strengths, figure 17. Figures 12 & 13 show high strength joints produced at slightly slower speed, confirmed by figure 14. In these cases, there appears to be no flow of substrate material and hence no disruption of the micro-fluidic channels. At lower speeds and higher line energies, other interesting effects are noted. In particular, figures 15 & 16 show that the film is has been pulled into the channel and melting and disruption of the channel has occurred. It should be noted that the film still appears to be very well bonded onto the substrate.

Figure 14 Sealed micro-channel, 95 mm/min

Figure 15 Smaller sealed micro-channel, 95 mm/min

Figure 16 X 1500 magnification of joint line from fig. 13
These results were then applied to sealing of structured CD’s. Figure 18 shows typical features that have been sealed with the 20 µm film using a FAP System at 10 watts.

6 Discussion

The inherent controllability of the diode laser welding processes demonstrated here has produced repeatable full strength thermal bonds between the 20 µm films and the polycarbonate substrates. It was noted that using a round spot, figure 11, appeared to give slightly less controllability than using the line source, figures 12 & 13. This is typically not easy to achieve with other thermal processes on these materials. This is certainly not easily achieved when joining thin films to thicker substrates such as the 1.2 mm thick compact discs.

The optical clarity of the bonded areas also suggests that rapid solidification has produced an amorphous structure in the film, this structure is normally associated with excellent mechanical properties, and again, is not easily achieved using conventional thermal welding techniques.

7 Conclusions

A possible new application area for diode laser transmission welding has been demonstrated, the sealing of micro-fluidic devices.

Excellent weld quality has been confirmed by a combination of materialographic examination and mechanical testing.

It has been shown that a derivative of the laser transmission welding process is able to seal these micro-molded devices without destroying the structure of these devices.

Only low laser power is required to produce these welds at low speed.

8 References