

Analysis of Melting Point Depression in Biodegradable Polymers Using Supercritical Carbon Dioxide by Golden Gate IR and High Pressure DSC.

D. Westerman*¹, S. P. Nalawade², G. A. Leeke¹, D. W. Grijpma², R. C. D. Santos¹

¹*Department of Chemical Engineering, University of Birmingham, B15 2TT, UK.*

²*Department of Polymer Chemistry and Biomaterials, University of Twente, The Netherlands.*

d.westerman@bham.ac.uk

Abstract

Poly(L-lactide), triblock copolymers based on polylactide and poly(trimethylene carbonate) and their stereocomplex (enantiomeric mixture of poly(L-lactide) and poly(D-lactide)) were subjected to carbon dioxide (CO₂) over a range of temperatures and pressures in order to investigate their effect on melting point. Golden gate infra-red spectroscopy (FTIR) experiments were performed isobarically at 0, 6, 12, 17 MPa pressures of carbon dioxide over a thermal gradient of 25 – 250 °C in order to visualize the degree of chain mobility in the polymer films. Attention was paid to the carbonyl shift at approximately 1750cm⁻¹ and a C-O marker region for CO₂ at approximately 1100 – 1200 cm⁻¹. Absolute melting points were analysed by high pressure differential scanning calorimetry (DSC) running isobarically at 0, 5 and 9 MPa over a thermal gradient of 25 – 250 °C. The pressure range of the FTIR was greater than that of the DSC (0 - 17 MPa and 0 - 9 MPa respectively) although a linear extrapolation of the DSC data relates well to the higher pressure FTIR observations of increased chain mobility brought about by a phase change.

The magnitude of the melting point suppression was found to be related to the degree of crystallinity, which is in turn related to the enantiomeric form used, and molecular weight of the polymer. A maximum reduction of 40 °C was found for a 65/35 ratio of Stereocomplex of poly(L-lactide-trimethylene carbonate-L-lactide) and poly(D-lactide-trimethylene carbonate-D-lactide) at 9 MPa CO₂ while a 50/50 enantiomeric ratio only resulted in a melting point suppression of 11 °C at the same pressure.

Introduction

The use of supercritical CO₂ as a foaming agent in polymer processing is well known and has found recent applications as a melt processing aid and as a porogen for various polymers [1,2,3]. The aim of this work is to investigate the use of CO₂ as a melting point (mp) and viscosity suppressant for various high and low molecular weight (mw) biodegradable polymer classes (with varying degrees of crystallinity) for use in medical applications. Thermal and mechanical shear degradation of these types of polymers during processing is a major problem and has hindered their development to date.

Supercritical CO₂ is ideally suited to this application due to its bio-compatibility, inert nature, gas like diffusivity and its liquid like density. Furthermore, it is intrinsically safe to use and has a sufficiently low critical point (7.38 MPa and 31.1 °C) to be easily achievable in practice and can be readily introduced into a polymer melt.

Synthesis of biodegradable high molecular weight polymer films of crystalline enantiomeric polylactides (L- or D-) and amorphous poly(trimethylene carbonate) and of low molecular weight novel tri-block copolymers based on lactides (L- and D-) and trimethylene carbonate was performed at the University of Twente, The Netherlands and supplied to The University of Birmingham, UK for analysis.

Polymer Synthesis

A series of polymer films were produced by the Protec project partner at the Dept. of Polymer Chemistry and Biomaterials, University of Twente, The Netherlands, according to standard synthesis procedures. The films selected for analysis ranged in their degree of crystallinity and molecular weight. This work discusses the results obtained from a Polylactide which was a mixture of L- and D-lactide (PLA), a

Poly(L-lactide), and a Stereocomplex of poly(L-lactide) and poly(D-lactide) which are termed PLA, PLLA and ST respectively.

Film Preparation

Films of the different polymers were prepared by the solution casting method and compression moulding. In the solution casting method, solutions of the polymers in chloroform (2 to 10% w/v) were cast on glass plates using a casting knife. After drying under ambient conditions for 1 week followed by drying in a vacuum oven for 1 week, 50-100 μm thick films were obtained. Films of a thickness of 0.5 mm were compression moulded in prefabricated templates. In each template around 2.8 g of polymer was used for a mould having dimensions of 2.5 cm x 12 cm. After moulding, the films were kept in vacuum sealed bags and the semi-crystalline polymers were annealed in an oven at 65 °C for 30 minutes to aid the re-crystallisation process.

Experimental Instruments

Golden Gate FTIR

A Perkin Elmer FTIR instrument with liquid nitrogen cooled optics was used with an attached Golden Gate MkII ATR pressure cell. The experimental procedure of sample loading, rates of increasing pressure and temperature and equilibrium time between scans were constant throughout. All scans reported here were performed using identical instrument settings.

High Pressure DSC

A Mettler Toledo 827e instrument was used for all DSC work, the pressure range investigated was from ambient to a maximum of 9 MPa. All experiments were performed isobarically from 25 °C to 250 °C with a temperature ramp of 10 °C/min. During the experiment it was necessary to bleed off CO₂ during the heating ramp via a manually controlled vent valve. All reported melting points are taken as the maxima of the endothermic peak. It must be noted that a significant baseline noise is evident with increasing pressure, this is due to thermal currents within the sample cell interfering with the heat flow measurement.

Results

Figures 1-7 show the effect of increasing temperature at a constant pressure on PLLA and PLA films. In general terms the trend of increasing temperature reduces the shoulder peaks at 1040 cm^{-1} and 1130 cm^{-1} is common throughout. This region is used to determine the point at which a plasticizing effect is occurring and allow a depression of mp and glass transition temperature (T_g) to be followed with increasing temperature and pressure.

Shifts in peak maxima to higher wavenumbers of both the carbonyl and marker peaks are observed with altering the temperature and pressure, this shift is confirmed as the onset of phase changes within the polymer by high pressure DSC.

The general trend of a broadening of shoulder peaks of the prominent ca.1080 cm^{-1} peak with increasing temperature and pressure is significant (in the absence of an absolute spectral interpretation) because it is indicative of the onset of a phase change. Residual organic solvent effects from film preparation were discounted with the testing of a compression molded film and the persistent trend of these peaks (Figure 8). The broadening of these shoulders is attributed to the presence of CO₂ as a peak narrowing occurs slowly over time with depressurization while CO₂ desorbs from the polymer. The carbonyl peak profile and shift at ca 1750 cm^{-1} is a potentially more reliable region of interest since it is more easily quantifiable and its assignation can be confirmed with chain mobility.

Figure 9 shows the effect of liquid CO₂ on the PLLA polymer film below T_g . There is a significant shift in the carbonyl peak from 1748 cm^{-1} to 1755 cm^{-1} with the introduction of CO₂ at all pressures indicating a reasonably strong affinity with the polymer where temperature is discounted.

The DSC trace (Figure 10) show the stereocomplex film. The same sample was run repeatedly in order to observe any degradation effects. Initially the sample was run in the absence of CO₂ and the mp was observed at 182°C, the same sample was then run at 5 MPa and the mp was reduced to 168°C. After

cooling and allowing equilibrium at ambient temperature and pressure the sample was then run in the absence of CO₂ and the mp had returned to 182°C. Further runs on the same sample at 4MPa, 3MPa and 2MPa showed an incremental reduction in mp of the order 2-3°C per 1 MPa increase in CO₂ pressure. This trend is consistent for the other polymer films analysed and the results are shown in table 1.

Figures 11 shows the IR spectra of the same stereocomplex film at ambient pressure with increasing temperature. The shift of the carbonyl peak from 1745 cm⁻¹ to 1750 cm⁻¹ with increasing temperature clearly show the onset of the melting point as plasticization occurs. Figures 12 and 13 show the effect of increasing temperature at 6 and 17 MPa CO₂ pressure respectively on the carbonyl regions.

The effect of increasing pressure at an ambient temperature was also investigated in order to show the effect of liquid CO₂ on the polymeric chain mobility in the stereocomplex and PLLA (Figures 14 and 15 respectively). It can be seen that the CO₂ has entered the polymer chains and is having a significant effect on the behavior of the film. The PLLA film shows the greatest effect as would be expected given that it is the least crystalline of the polymers discussed here. The more crystalline structures of PLA and the stereocomplex are more resilient to chain mobility than the amorphous nature of the PLLA.

The magnitude of the carbonyl shift for the PLLA was greater with the introduction of CO₂ than if it was merely melted. This is evidence of a temperature independent lubricating effect of the CO₂ on the polymer chains (with a significant drop in viscosity) since it separates the polymer chains. This is shown in Figure 15 where the carbonyl shift has increased from 1740 – 1755 cm⁻¹ with increasing pressure at ambient temperature, this is in contrast to Figure 16 which only shows a carbonyl shift from 1745 – 1750 cm⁻¹ at ambient pressure and increasing temperature. This effect is also seen for PLA and the stereocomplex although to a much lesser degree.

The effect of CO₂ on the PLA film carbonyl stretch, although this is less distinct than for the stereocomplex or the PLLA it is still clear that there is an interaction, with a carbonyl peak shift from approximately 1750 cm⁻¹ to 1755 cm⁻¹. The DSC data shows a significant melting point reduction from 154 °C to 122 °C at 9 MPa CO₂.

Table 1 shows the melting point of the polymer films in the absence and presence of CO₂ from high pressure DSC data. When this is plotted and extrapolated it is clear that the PLA shows the least effect with the addition of CO₂, this is to be expected since it has a relatively highly crystalline structure when compared to the stereocomplex or the PLLA. A melting point suppression of 20 – 30 °C is achieved depending on the grade of polymer at a pressure of 9 MPa. When extrapolated to a realistic degree it is possible to envisage a process temperature of *ca.*130 °C for medical grade polymer at 17 MPa. The Stereocomplex shows a melting point suppression of *ca.* 25 - 30 °C at 9 MPa, This is comparable to the industrial grade PLA even though it is more amorphous in structure because of its significantly higher molecular weight. The PLLA however shows the greatest depression, the melting point drops by 47 °C at 9 MPa as it has the favourable characteristics of a lower molecular weight than the stereocomplex and a more semi crystalline structure than the pure PLA.

<i>Sample Ref.</i>	<i>DSC mp °C 0 MPa</i>	<i>DSC mp °C 5MPa</i>	<i>DSC mp °C 9MPa</i>
<i>Stereocomplex (Batch 1)</i>	181	173.2	152
<i>Stereocomplex (Batch 2)</i>	178.6	168.6	153
<i>PLLA</i>	177.8	164	130
<i>PLA (Medical Grade)</i>	152.4	142.3	129.7
<i>PLA (Industrial Grade)</i>	154.3	143.7	122

Table 1 Melting point data from High Pressure DSC

In conclusion, it is apparent that there is a significant effect of CO₂ addition on both the melting point and viscosity of the polymers discussed here. Furthermore, it is clear that the molecular weight and the degree of crystallinity have a significant effect on the melting point depression. For medical applications, it is desirable to maintain a crystalline (or semi crystalline) structure in order to maintain the physical performance of a polymer product whilst minimizing thermal and shear degradation. Typical processing

temperatures for medical grade PLA are in the order of 200 °C, this can be successfully reduced by a significant degree depending on the processing pressure with the introduction of CO₂.

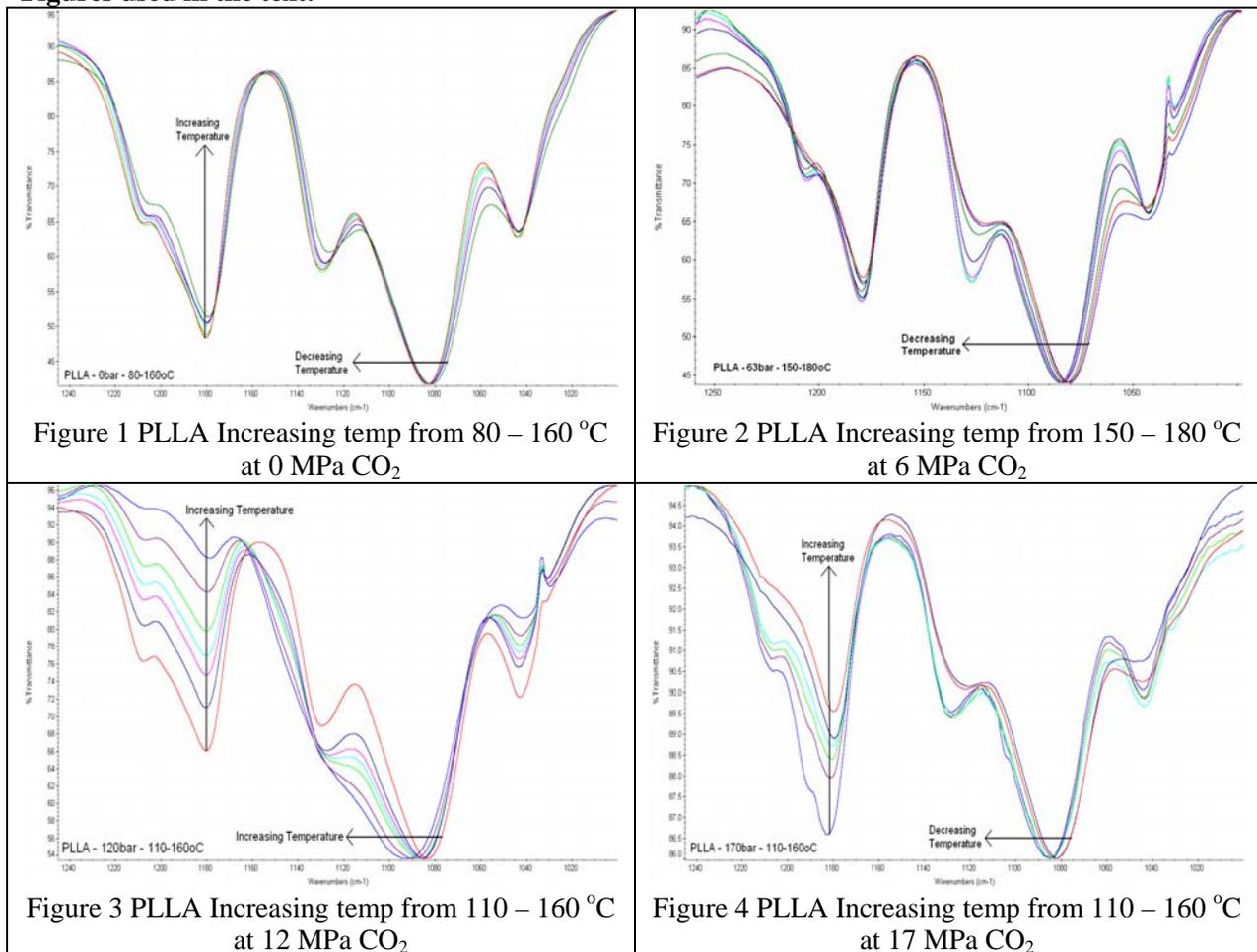
Acknowledgements

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Figures used in the text.



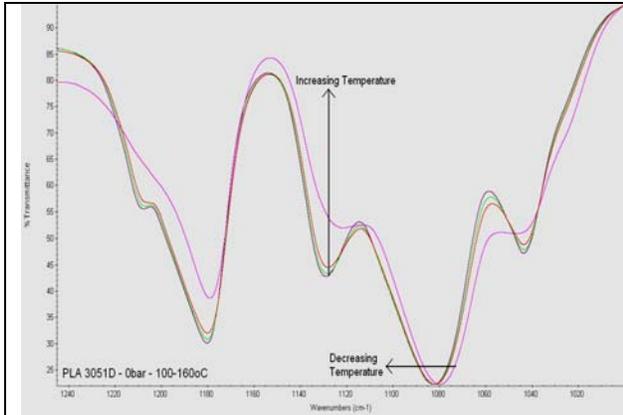


Figure 5 PLA Increasing temp from 100 – 160 °C at 0 MPa CO₂

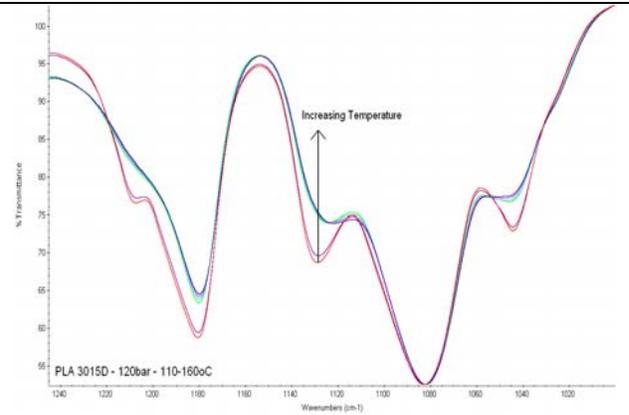


Figure 6 PLA Increasing temp from 110 – 160 °C at 12 MPa CO₂

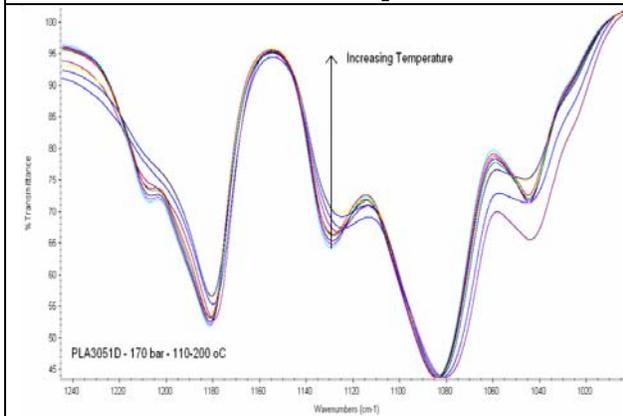


Figure 7 PLA Increasing temp from 110 – 200 °C at 17 MPa CO₂

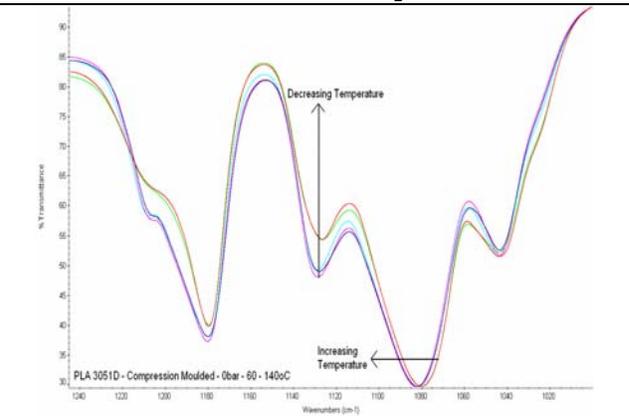


Figure 8 Compression moulded PLA at 0 MPa CO₂

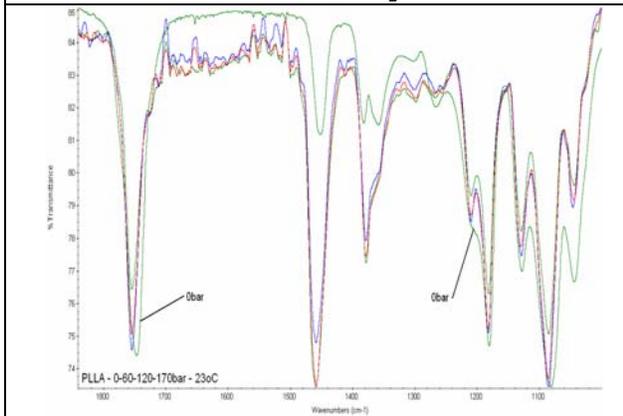


Figure 9 PLLA Increasing pressure from 0 – 17 MPa at ambient temp

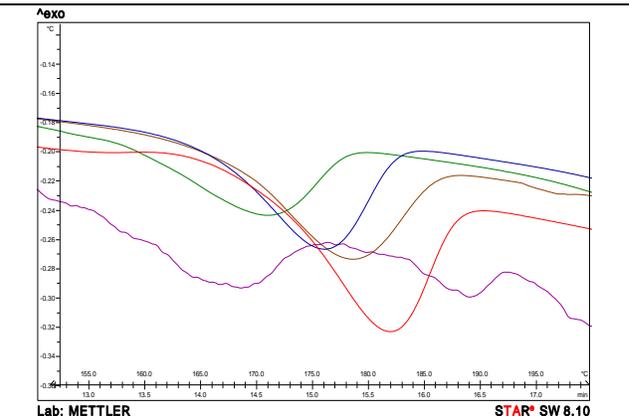


Figure 10 Stereocomplex Film with increasing CO₂ pressure from 0 – 9 MPa

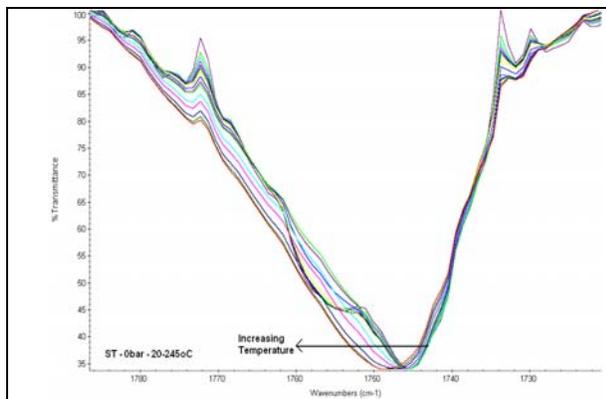


Figure 11 Stereocomplex with increasing temp from 20 – 245 °C at 0 MPa CO₂

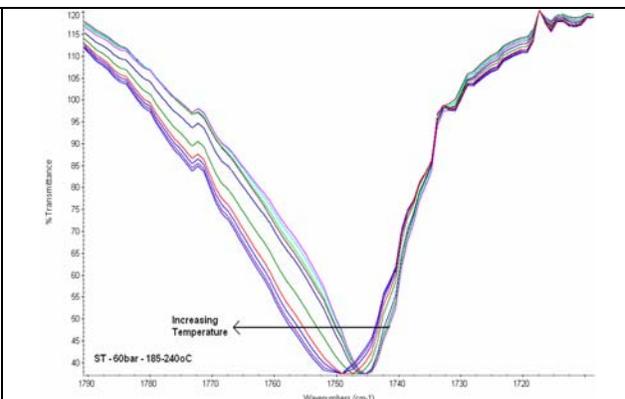


Figure 12 Stereocomplex with increasing temp from 185 – 240 °C at 6 MPa CO₂

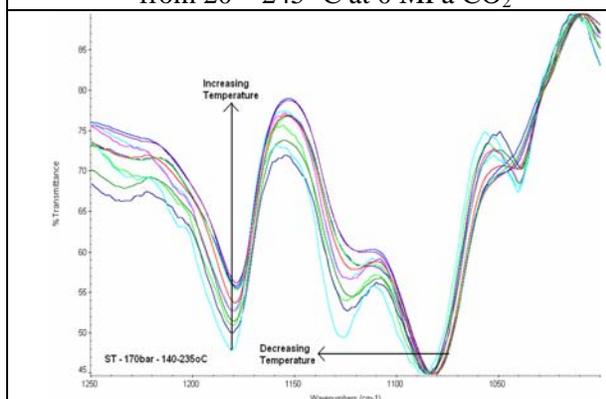


Figure 13 Stereocomplex with increasing temp from 140 – 235 °C at 17 MPa CO₂

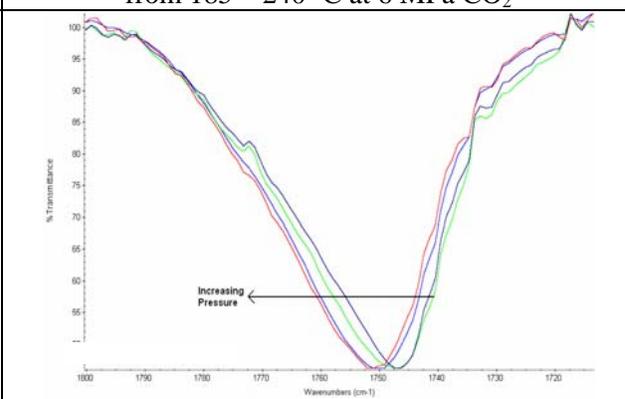


Figure 14 Stereocomplex with increasing pressure from 0 – 17 MPa at ambient temp

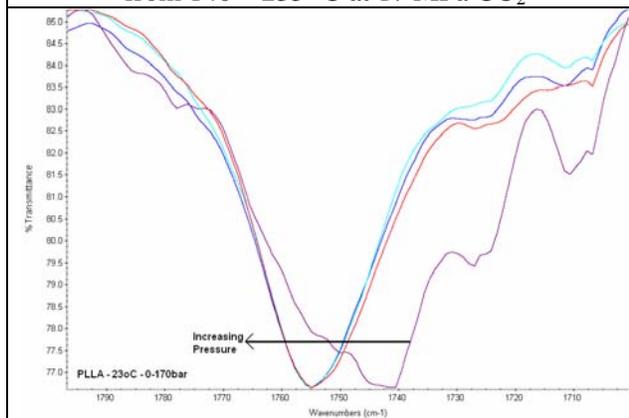


Figure 15 PLLA with increasing pressure from 0 – 17 MPa at ambient temp

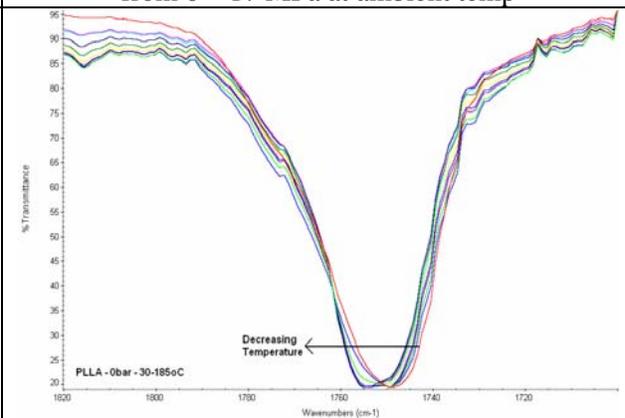


Figure 16 PLLA with increasing temp from 30 - 185 °C at ambient pressure