

PROPERTIES OF POLY(LACTATE ACID) CHAINS VIA MULTI-SCALE DYNAMIC SIMULATIONS, USING ATOMISTIC AND COARSE-GRAINED MODELS

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ABSTRACT

We present results from ongoing hierarchical multi-scale Molecular Dynamics (MD) simulations of poly(lactate acid), PLA, chains. First, a fully atomistic OPLS-based force field, PLAFF3, has been utilised to build amorphous structures of L-PLA of various molecular weights from decamer to 100-mer. The structures have been relaxed and subsequently simulated at the isothermal-isobaric ensemble at atmospheric pressure and temperatures from 200 °C down to 120 °C, covering a range between commonly employed conditions of PLA synthesis and target specifications for the pilot plant production system, respectively. Then, a coarse-grain, CG, model of PLA, in which monomers are represented as single interaction sites, has been developed by analyzing the atomistic data *via* the Iterative Boltzmann Inversion technique as implemented in an in-house software package. The CG force field is capable of exploring longer time scales and larger systems that would require excessive computational resources when simulated with atomistic resolution; the atomistic force field, on the other hand, can capture PLA properties with higher accuracy. The CG PLA model is to be compared to the detailed atomistic model in terms of predicted properties as functions of PLA molecular weight.

INTRODUCTION

PLA is a biodegradable polymer that can be synthesised from recycled biowaste. Thanks to its physical properties, PLA can be used as biocompatible and environment-friendly plastic with a range of applications extending from biomedicine to packaging and other routine daily usages. In this work, we are interested in optimising a process of PLA synthesis based on ring-opening polymerisation, at the pilot-plant level.

Thorough knowledge of PLA properties is required in order to optimise its synthesis as well as design PLA-based end products. Polymer properties depend strongly on molecular weight; measuring them experimentally can be time- and cost-ineffective. Empirical correlations can link properties with chemical structure, but they are usually subjected to large uncertainties.

Molecular simulation methods (Molecular Dynamics, Monte Carlo) offer an attractive alternative: provided a reliable molecular model is available, these methods are often capable of accurate prediction of a wide range of macroscopic properties. In this work, we employ Molecular Dynamics (MD) simulations as implemented in the well-known gromacs software package^[1], to study the structural, thermodynamic and other properties of L-PLA.

THEORY

In MD simulations, molecules are described as collections of sites (atoms or groups of atoms) that move subjected to forces stemming from site-site interactions. These forces correspond to appropriate potential energy functions such as ‘bonded’ potentials that preserve the molecular connectivity and average configuration at thermodynamic equilibrium as well as ‘non-bonded’ ones (e.g. dipole interactions described by partial charges, and van der Waals forces). The set of these potentials is the system’s ‘force field’ or model; its empirical parameters have a certain physical significance (bond length, atom diameter etc.) and they are fine-tuned by fitting to known experimental data for the same or similar materials or quantum mechanical calculations for oligomers of the same family.

A system of molecules under study is set up as a cubic or other kind of unit cell interacting with replicas of itself in all directions, in order to simulate interactions in the bulk material in a realistic manner. Given the initial conditions (positions and temperature-dependent velocities) the set of equations of motion of the interaction sites is solved numerically while pressure and temperature can be held constant with the aid of appropriate algorithms. Then, the system trajectory is obtained as a collection of successive system snapshots; this is further subjected to processing based on the principles of Statistical Mechanics and specific properties can be, thus, predicted.

Force fields of fully atomistic detail allow more accurate predictions at the cost of more time-consuming calculations and additional requirements in memory and disk space. As a compromise, one can use coarse-grain models where whole groups of atoms (e.g. monomers) can be replaced by a single site. Numerous coarse-graining methods exist. Iterative Boltzmann Inversion^[2-3] (IBI) is an established coarse-graining technique that relies on the link between free energy differences, ΔA , and group-pair radial-distribution functions, $g(r)$:

$$(1) \quad \Delta A = -k_B T \ln g(r)$$

In this way, a temperature-dependent free energy function can be obtained; this is further refined in an iterative fashion, by comparing the output of coarse-grain simulations with the target (atomistic) results. Bonded coarse-grain potentials are also obtained by inverting the corresponding distributions.

SIMULATION DETAILS

PLA monomers exist as L or D stereoisomers. Natural PLA exists as L-isomer and this form will also be synthesised for the purpose of biocompatibility. The so-called PLAFF3^[4] force field was selected for our simulations. The parameters of this model have been optimised in order to reproduce the energy minima of oligomers as predicted by quantum mechanical calculations; the polymer conformations in the crystalline state; the amorphous melt density; the thermal expansion coefficient; and the glass transition temperature. In this model, molecules are described at the fully atomistic level.

We have simulated structures of L-PLA with degree of polymerisation (DP) equal to 10, 25 and 50. Simulations for DP = 100 are under way and will be presented in forthcoming publications. We started with a thermodynamically equilibrated (at 300 K and 1 at) orthorhombic structure of 32 50mer chains that was simulated at successively higher temperatures (373, 473, 523 and 573 K) for 20 ns in order to ‘melt’ the structure and eliminate structural correlations with the initial configuration. Then, the system was cooled down and properties were determined for the range between 393 and 473 K that defines the desired

process temperature and the one where synthesis is typically carried out. The final simulations lasted 25 ns, the time step was 1 fs and pressure was 1 at. The same procedure applied for the 10mer and 25mer systems that were generated by disabling the bonded potentials between the appropriate successive monomers. Of note, although atoms carry partial charges, all monomers are electrically neutral. In the simulations reported in this work, all monomers are identical. Similar calculations are under way in which the end monomers were replaced by appropriate acid-, alcohol-, methyl ester- or methoxy-terminated terminal groups. In this way, the effect of the particular groups can be determined. Finally, the 100mer structure was generated by placing identical crystalline systems in a row along the axis of the PLA chains and enabling additional bonded potentials between two neighboring chains of the adjacently placed unit cells.

A number of structural, thermodynamic and other properties (including radius of gyration, radial distribution functions, density, expansion coefficient) were determined in the final simulations. These were obtained as time series of instant values that allowed to identify the time required for thermodynamic equilibrium to be established; the non-equilibrated portion was discarded and averages were obtained over the remainder.

Radial distribution functions served as the basis for the generation of a coarse-grain force field in which whole monomers are represented as single interaction sites. The method of Iterative Boltzmann Inversion (IBI) as implemented in an in-house software package, was employed to generate a coarse-grain force field based on a single kind of interaction sites, corresponding to the L-monomer repeat unit.

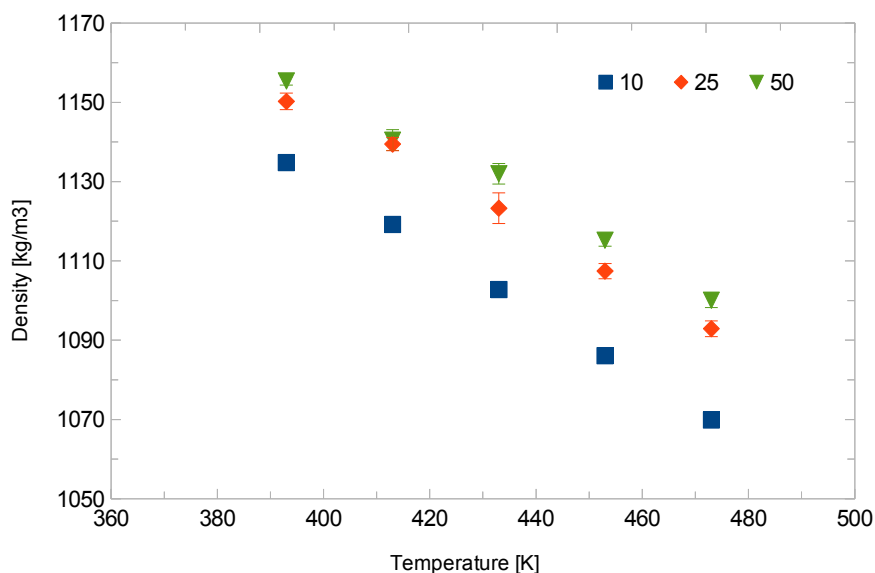


Figure 1. L-PLA density as a function of temperature, for DP equal to 10, 25 and 50.

RESULTS AND DISCUSSION

The density of L-PLA as a function of temperature, is displayed in Fig. 1 for L-PLA 10-, 25- and 50mers. Linear extrapolation to 300 K yields 1211.1, 1225.3 and 1227.6 kg/m³, respectively; the latter is less than 2% off the high-polymer experimental density of 1250 kg/m³. The thermal expansion coefficient can be obtained by numerical differentiation, giving 6.9 to 7.5, 4.7 to 7.1 and 3.7 to 7.5 × 10⁻⁴ K⁻¹, for the 10-, 25- and 50mer, respectively. The large range of

expansivity values for the 25mer and especially the 50mer suggests that longer simulations would be beneficial for proper sampling. The 50mer appears to be close to the threshold where thermodynamic properties converge to the polymer limit.

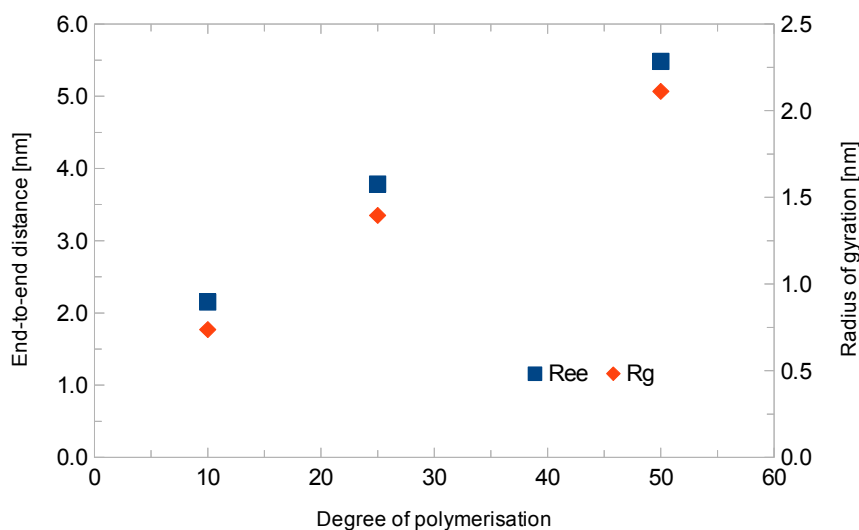


Figure 2. L-PLA end-to-end distance and radius of gyration (averaged over temperatures from 393 to 473 K) as a function of number of monomers.

The end-to-end distance, R_{ee} , and radius of gyration, R_g , are typical molecular size indicators. Their values vary strongly with molecular weight whereas they exhibit a very slight decrease with temperature. The points in Fig. 2 have been obtained as averages over the examined temperature range wherein the error bars hardly exceed 2% for R_{ee} and 0.5% for R_g ; they vary approximately with the 0.66 and 0.58 power of molecular weight, respectively, suggesting that the systems are close to albeit not fully equivalent to random coils. The eigenvalues of the gyration tensor indicate a close to spherical ellipsoid shape with the ratio of maximum over minimum axis ranging between 1.10 and 1.45.

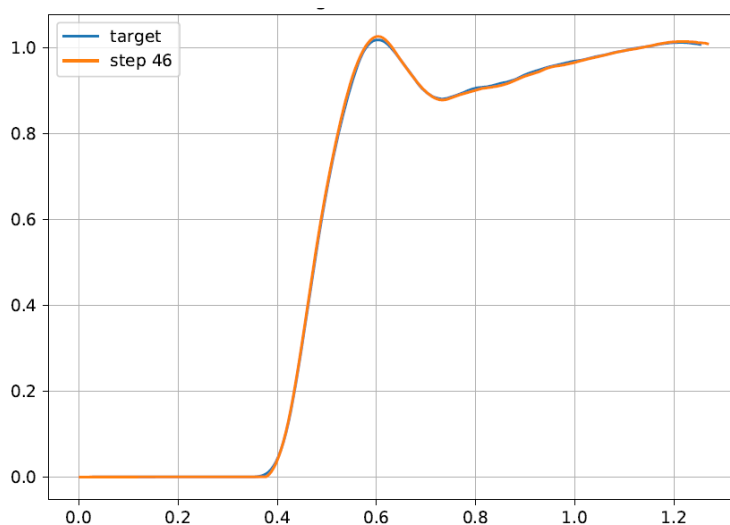


Figure 3. Monomer pair radial distribution function from atomistic simulation of PLA 50mer ("target") at 473 K and its near-convergent IBI-based coarse-grain counterpart.

Monomer-monomer radial distribution functions, $g_{mm}(r)$, assume a form that is typical of liquid or amorphous materials, ensuring that the system has sufficiently departed from its initial crystalline state. IBI calculations based on the $g_{mm}(r)$ functions of the atomistic trajectories of the 50mer (the system closest to the high-polymer limit), are under way. Figure 3 compares the atomistic and coarse-grain $g_{mm}(r)$ at 473 K, indicating almost perfect matching that signals the imminent convergence of the iterative procedure. Similar results have been obtained for the bonded distributions concerning the distance (coarse-grain bond length), angle and torsion angles formed by two, three and four consecutive monomers, respectively. The resemblance between target and coarse-grain curves is a promising result regarding the ability to predict thermodynamic and structural properties of PLA. Predictions of dynamic and transport properties are generally expected to deviate from their actual values when using coarse-grain representations; however, these are of lesser importance in the particular study.

CONCLUSIONS

Molecular Dynamics simulations have been carried out in order to determine a range of properties of L-poly lactide, in the context of a multi-scale approach for the optimisation of PLA synthesis at a pilot-plant level. Atomistic simulations are capable of providing a wealth of information about macroscopic and microscopic properties of the material as functions of molecular weight and conditions. Furthermore, coarse-grain models can be fine-tuned to match the free energy differences of atomistic systems; in this way, calculations for the prediction of thermodynamic properties can be considerably accelerated. Ongoing and future work includes simulations of higher molecular weights (100mer and beyond) as well as comparison of atomistic and coarse-grain calculations based on both our model and an existing one from the literature^[4].

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