Preliminary study of early time dynamics during pulsed laser interaction with a CH ablator target

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Abstract

It is well known that a critical area of concern to inertial confinement fusion (ICF) is target nonuniformities due to their unstable growth. In direct-drive ICF experiments, the process starts when a low intensity pulse illuminates the ablator. Three-dimensional Multiphysics finite element modelling and simulations were recently carried out by our team to explore the influence of the thermoelastoplastic (TEP) and melting phases during the ablator's heating considering its intrinsic real TEP properties. In this work, to simulate the initial phases of solid-to-plasma transition, a ns pulsed laser interacts with a polystyrene (CH) target-sample. A 3-mm diameter 100-μm-thick planar disk of CH polymer is irradiated by a single laser beam of 6 ns pulse duration. To simulate the hydrodynamic response of the target, the first-principles equation of state (FPEOS) of polystyrene is used. For the TEP mechanical response of the heated solid an accurate strength material model is considered. The results of this study aim to contribute towards the comprehension of the transition from solid to plasma phase of the target.

In direct-drive ICF experiments, the process starts when a low intensity pulse illuminates the capsule [1-4] that consists of a cryogenic deuterium–tritium (DT) shell covered by an ablator layer. The generated shock wave compresses the target. Nonuniformities in the laser drive, generated via laser speckle and beam-to-beam intensity variations, may seed hydrodynamic instabilities such as the Richtmyer-Meshkov and the Rayleigh-Taylor [5]. Moreover, the energy transfer of the laser-intensity modulations to the shock front, which is called the laser imprint, depends strongly on the initial plasma formation [6].

In this work, preliminary FEM (Finite Element Method) simulations to study the early time dynamics during the pulsed laser interaction with a CH ablator target are performed. A nanosecond (ns) pulsed laser interacts with a CH target-sample. The sample geometry is similar to the work in [7], where direct-drive measurements of laser-imprint-induced shock velocity nonuniformities are performed. Three-dimensional Multiphysics FEM modelling and simulations [3] are carried out during the ablator's heating initial phases considering its intrinsic real TEP properties.

A 3-D coupled mechanical/thermal FEM model is developed using the LS-DYNA finite element software. A 3-mm diameter 100-μm-thick planar disk of CH polymer is irradiated by a single laser beam (532 nm) of 6 ns pulse duration while the laser spot radius is 425 μm. The half symmetric geometry of the CH target is modelled. To simulate the hydrodynamic response of the polystyrene target, the analytical Gruneisen and tabular multiphase FPEOS [8] are used and coupled with a Johnson-Cook strength material model that considers the elastoplastic effects. The CH FPEOS is multiphase and allows for the description of all the states of the matter: solid, liquid, gas, plasma, and their transitions. Temperature dependent properties of the thermal expansion, thermal conductivity and specific heat, the latent heat of melting as well the optical properties of polystyrene for 532 nm are also considered.

In the first set of simulations, the Grüneisen EOS is used for the whole volume of the target. The simulations show that in the central laser irradiated region the pressure and temperature increase rapidly, and the material reaches the melting or vaporization temperatures faster than the remaining part of the target. Thus, higher temperatures and lower densities prevail. In contrast, at the outer region of the target, for dimensions higher that the laser spot, lower temperatures, and higher densities are computed. Based on the feedback of the initial simulation results using the Grüneisen EOS, the target is divided to two regions. The FPEOS for CH is used in the central laser irradiated region, assuming the same radius with the laser spot. At the outer region, where temperature gradients are lower, the Grüneisen EOS is used. In the central region, the limits of the variables of temperature, density and pressure are defined by the feedback of preliminary numerical simulations using the Grüneisen EOS. Moreover, the FPEOS tabular data of pressure in relation to energy are interpolated for each density by a polynomial to obtain the needed values following the methodology published in the supplementary material of [9].

The simulation results show that the needed laser fluence for the central irradiated region to reach the melting temperature (513 K) is approximately 1 kJ/cm^2, which is significantly higher than a metallic material such as gold, where a fluence of 0.1 J/cm^2 is demanded [3].

This difference is attributed mainly to the very low value of the absorption coefficient of the polymer compared to metals, and due to its low thermal conductivity. The needed laser fluence for the central irradiated region to reach the boiling temperature (703 K) and the initiation of plasma formation (≥1000 K) [8] is 1.7 kJ J/cm^2 and 4 kJ/cm^2, respectively. Results of the irradiated target, 23 ns after the initiation of target irradiation, when the maximum temperature is observed and plasma is formed, for the temperature, plastic strain, density and pressure distributions are shown in Figures 1a, b, c and d, respectively. In the central laser irradiated region, the maximum temperature is more than 1000 K, while the density decreases to 880 kg/m^3 (solid density 1055 kg/m^3). The maximum tensile stress is 218.9 MPa, higher enough than the yield tensile strength of polystyrene (55 MPa) and the maximum compressive stress is 98.1 MPa.

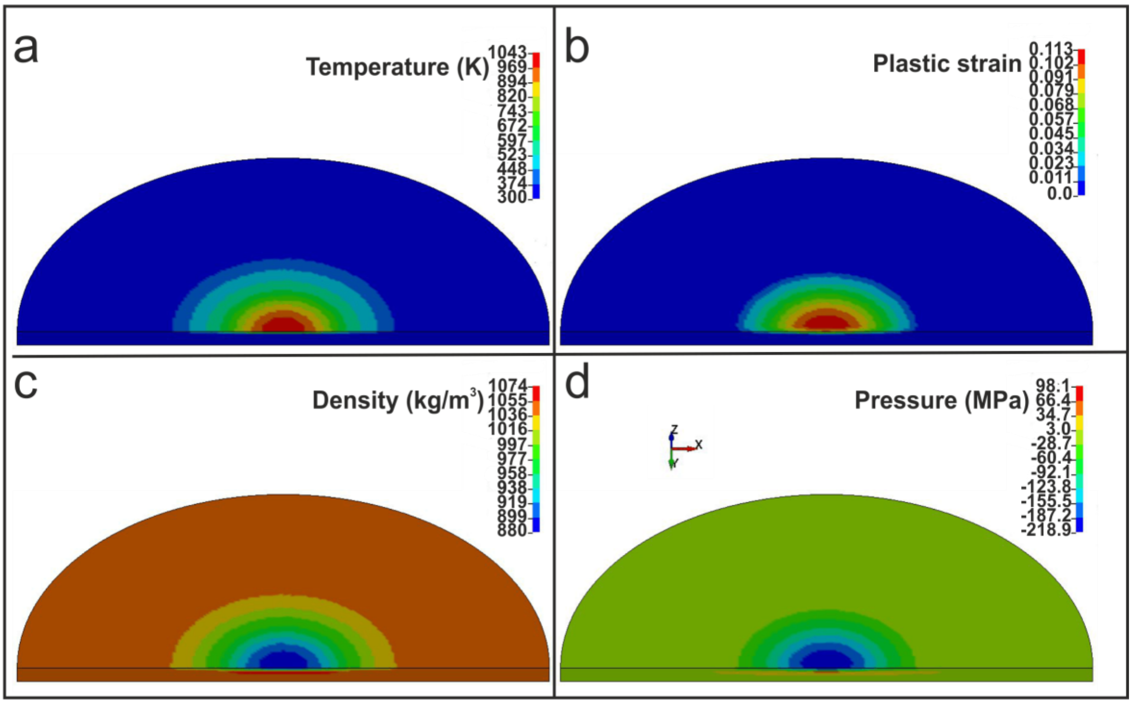

Figure 1. a) Temperature, b) Plastic Strain, c) Density and d) Pressure distribution results at 23 ns after laser irradiation starts

Figure 2a shows the displacements along the y-normal direction at 45 ns from the laser irradiation initiation. Longitudinal waves (LW) are apparent. Figure 2a, shows two typical selected model nodes (in yellow color), at 10 μm and 90 μm below the surface. The temporal evolution of the y-displacement for these nodes is demonstrated in Figure 2b. One can measure that the relative velocity of the LW is ~2200 m/s, which is near to the longitudinal speed of sound value of 2350 m/s in polystyrene.

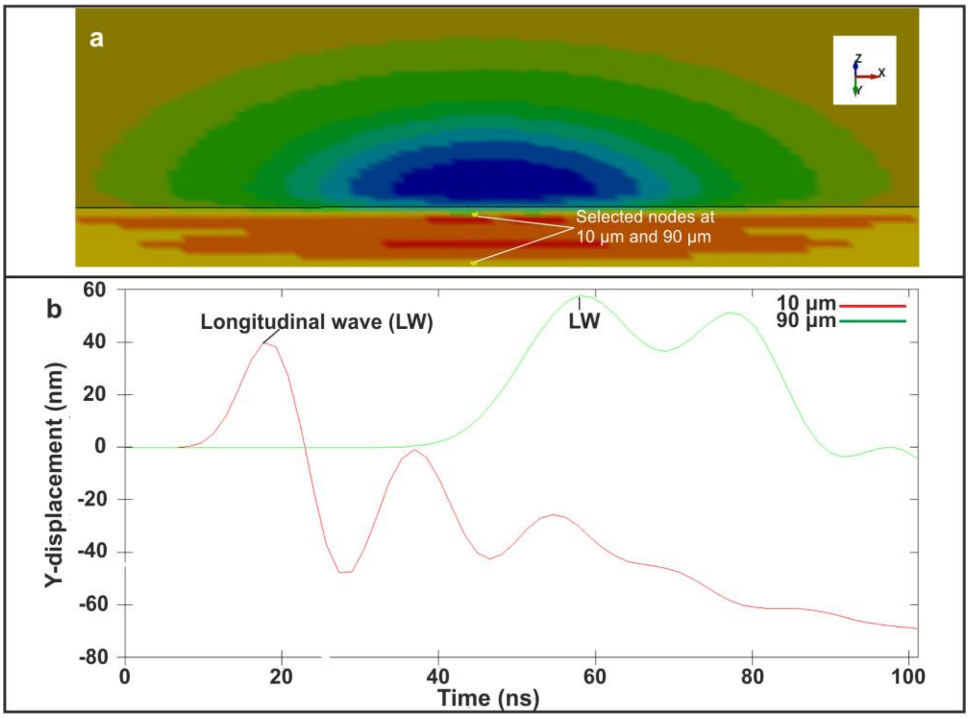

Figure 2. a) Displacement along the y-normal direction at 45 ns, b) Temporal evolution of the y-displacement for 10 μm and 90 μm from the laser irradiated surface

The preliminary results of this study aim to contribute towards the comprehension of the transition from solid to plasma phase of the target and to become a precursor for understanding the initial stages of the laser imprinting process and the development and seeding of the instabilities.

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