Phase transformations (PTs) under high pressure and plastic shear are widespread in nature, physical experiments, and modern technologies. In order to study the effect of plastic deformations on PTs, a rotational diamond anvil cell (RDAC) and diamond anvil cell (DAC) without hydrostatic media are utilized, in which large plastic shear is superposed in the sample under high pressure. Such PTs are classified as strain-induced ones and they occur by nucleation at defects that continuously appear during the plastic deformation. By applying finite element approach, plastic strain-induced PTs in a sample in DAC and RDAC are investigated in detail. A large-strain model for coupled PTs and plastic flow is developed, which includes micromechanically based strain-controlled kinetics. First, detailed analyses of the coupled plastic flow and PTs are studied during loading, unloading, and reloading. Second, an extended version of the Coulomb and plastic friction model for multiphase material with evolving concentration of phases is developed to model contact interaction on the contact surface. Third, cases without and with deformable gasket are compared and effects of gasket’s size and strength are discussed. A new sliding mechanism at the contact line between the sample, gasket, and anvil called extrusion-based pseudoslip is revealed. Various experimentally observed effects are reproduced and interpreted. Possible misinterpretation of experimental PT pressure is found. The obtained results will allow one optimal design of experiments and conditions for synthesis of new high pressure phases.