Discrete simulation of the compaction and sintering of UOX and MOX powders

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Jury :

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Abstract : This work, conducted in collaboration with the Orano Melox recycling plant, is part of the context of the French nuclear industry, which plays a central role in the country's electricity production. The thesis focuses on the manufacture of nuclear fuel through the stages of compaction and sintering of nuclear powders: UOX (Uranium OXide) and MOX (Mixed OXide) fuels. Uni-axial compaction induces a heterogeneous density field in the pellet. This heterogeneity is responsible for radial deformation during the ejection and sintering stages (diabolo effect), requiring the manufacturer to rectify the lateral surface. The aim of the thesis is to develop a dedicated digital tool to simulate the geometry of pellets after compaction and sintering, particularly anticipating the effect of MOX composition.

The digital tool must take into account the granular nature of the powders, the mixture's composition, and the industrial conditions of the process. For this, the discrete element method (DEM) is used. This simulation method, which explicitly considers the granular microstructure of powders by modeling each particle individually, is explored in detail in this manuscript. Constitutive laws for compaction and sintering are discussed, as well as their application in the context of nuclear powders. We adapt a model that addresses high relative densities considering the effect of local density (calculated via Voronoi cells) on powder strain hardening.

The chosen approach to simulate the powder at the scale of an entire tablet involves representing MOX powder as consisting of two types of porous agglomerates: UO2 agglomerates and primary mixture (MP, a high-plutonium-content mix) agglomerates. This optimizes the computation time of the simulations and accounts for the composition of different mixes used by the industry.

Initially, the UO2 agglomerate is modeled. To do this, a database was generated, including thousands of simulations varying six material parameters. A machine learning model was developed and trained

with supervised learning to determine the set of material parameters that best match the available experimental data on UO2.

The MP agglomerate is modeled using simplifying assumptions. Once the UO2 and MP agglomerates are modeled, the simulation of single and double-effect compaction on UOX and MOX is carried out. The kinematics and industrial geometry of the pellets are considered. In particular, the phases of elastic unloading and pressure-assisted ejection are modeled. After the compaction stage, a density gradient is observed, resulting from the relative movements of the walls and friction between the walls and the powder. A radial deformation of the pellet is obtained from this stage.

At the end of the manuscript, sintering is addressed. This part, serving as a proof of concept, does not cover the entire complexity of sintering but allows for studying the influence of the density gradient on the final geometry of the tablet. Two models are proposed. The first involves simulating sintering via discrete simulation, taking into account diffusion phenomena at the contact scale. The second, much simpler, only considers the density map in the compacted pellet.