General assessment and radiation damage minimization of advanced structural materials for compact tokamaks

Abstract

The necessity of suitable structural materials is one of the main issues that concern advanced reactor (i.e. Gen IV and fusion) designers and scientists. Advanced reactor concepts foresee high temperature environments, strongly corrosive coolants and an exacerbated radiation environment due to fast neutrons and high fluences. This thesis explores such aspects in the framework of a transition from a pre-conceptual to conceptual design of Affordable Robust Compact (ARC) fusion reactor. ARC concept is the flagship of the high magnetic field path to nuclear fusion energy. In this work, the suitable structural materials for ARC core structures, namely the vacuum vessel, are assessed. Four most concerning issues have been identified in ARC core environment: high thermal loads and temperature, structural integrity, a deeply corrosive environment and elevated neutron loads with unpredictable effects. A reference alloy for each of the families considered is here taken. The work focuses on steels, Ni-based superalloys, V-based alloys and Multiple Principal Element Alloys (MPEAs). An accelerated analytical thermomechanical analysis is proposed to identify the materials with the best thermomechanical tradeoff properties. Ni-based superalloys and V-based alloys show the highest chances to survive ARC core environment, with Ni-based superalloys having an extreme structural resistance and V-based alloys a more optimized mechanical-thermal properties tradeoff. The corrosion issue is out of the aims of this thesis. However, some main aspects and possible solutions (i.e. coatings and corrosion control through beryllium doping) are taken from literature and briefly discussed. The work divides the irradiation aspects in three main studies. A neutron transport analysis, performed to assess the suitability of structural materials in the core environment. Ni-based alloys raised some concerns regarding their negative effect on the fuel cycle self-sustainability. Other alloys allow for more conservative results. Afterwards, the radiation induced activation of each alloy is estimated. In this instance, the study proposes some optimization techniques to minimize the expected radioactivity of irradiated materials. V-based alloys have the lowest achievable induced radioactivity, requiring disposal for less than a century. Ni-based superalloys would most likely require medium-level waste-like management strategies for a few centuries. Lastly, an advanced study on the primary radiation damage effects is proposed. The work aims to both assess the radiation resistance of the considered alloys and to provide some useful guidelines for the design of radiation-resistant advanced materials, like MPEAs. Results strengthen the hypothesis of a link between the potential energy landscape of a material and its radiation response, shedding light on the main driving mechanisms. It should be possible to identify the most radiation resistant alloys by characterizing their main element potential energy and defect migration energy barriers. While, for advanced and highly mixed materials, the heterogeneity in the energy barriers seem to be the driving parameter for designing a radiation resistant material.

Despite this work identifies V-based alloys and MPEAs as the most suitable for the purpose, because of the different technological readiness level, a different path is also suggested. A first version of ARC would probably rely on a Ni-based superalloy. The first ARC version will surely provide fundamental experimental data about its core environment effects on structural materials. The following, most efficient, versions of ARC should rely on better performing V-based alloys or advanced materials.