New affordable and tunable low-activation steel grades for structural materials applications

The Belgian Nuclear Research Centre SCK CEN developed a family of affordable low-activation steel grades that demonstrates superior properties to EUROFER97 (reference material in Europe for plasma-facing components in fusion applications). Its larger ductile range, higher strength and higher creep resistance offer a strong alternative/upgrade to EUROFER97 and can be applied in other applications for components requiring very high ductility (i.e. pipes) or very high strength (i.e. supporting plate/stiffening boards). The material's thermo-responsive traits allow post-production property adjustments, broadening its utility. In extreme heat scenarios, its microstructure changes predictably, beneficial for safety-critical structural assessments.

Description of the technology

One of the modern approaches in the optimization of mechanical properties of nuclear grade steels is based on exploiting computational thermodynamics to design the alloy composition and heat treatment. Remarkable examples of modified reduced activation ferritic/martensitic (RAFM) steels are the castable nanostructured alloys developed in USA, but not yet up-scaled to demonstrate the full potential as structural material. Belgium nuclear Research center and OCAS NV made efforts to develop new generation of RAFM steels by using computational thermodynamics coupled with strength modelling and high throughput experiments to down select the best grades as suggested by theory. It is demonstrated that refined precipitation with a high-volume density and a reduced width of martensitic laths, compared to the reference RAFM steels developed in early 2000th offers a better mechanical performance. The mechanical results confirmed the enhanced yield strength of the new alloys and greater toughness.

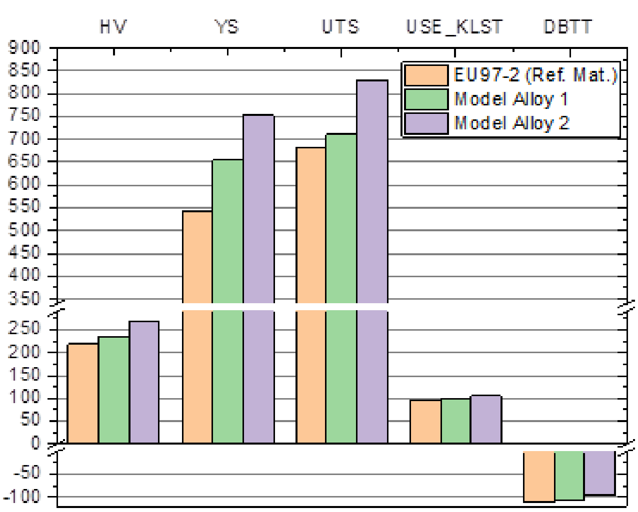

Fig.1. Comparison of mechanical properties of model alloys after HT 2 with EUROFER97. The values of USE are magnified by a factor of 10 to enhance readability of the data. Upper shelf energy of KLST samples was multiplied by a factor of 10.

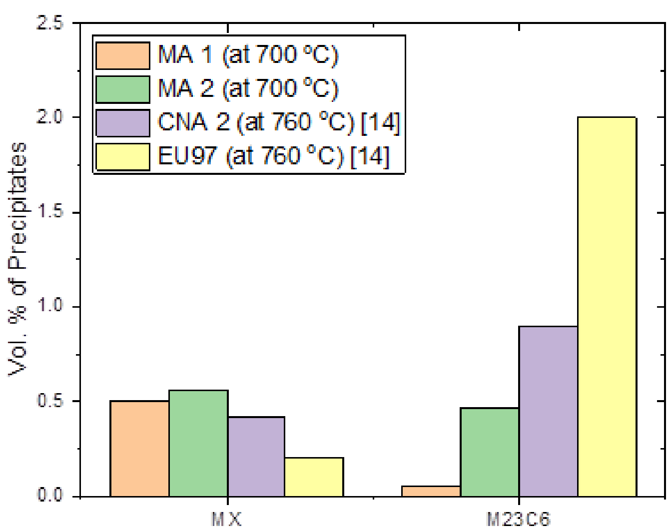

Fig.2. Volume percent of two kinds of precipitates (MX and M23C6), which explains why the advantageous properties were achieved.

New affordable and tunable low-activation steel grades for structural materials applications

The Belgian Nuclear Research Centre SCK CEN developed a family of affordable low-activation steel grades that demonstrates superior properties to EUROFER97 (reference material in Europe for plasma-facing components in fusion applications). Its larger ductile range, higher strength and higher creep resistance offer a strong alternative/upgrade to EUROFER97 and can be applied in other applications for components requiring very high ductility (i.e. pipes) or very high strength (i.e. supporting plate/stiffening boards). The material's thermo-responsive traits allow post-production property adjustments, broadening its utility. In extreme heat scenarios, its microstructure changes predictably, beneficial for safety-critical structural assessments.

Description of the technology

Moreover, even the ductile to brittle transition temperature (DBTT) of the developed alloys is superior compared to EUROFER97 – being currently the main structural steel developed for high temperature nuclear applications (e.g. for ITER) in Europe. These new grades can be qualified as nuclear grade (controlled minor alloying elements) by optimizing the content of carbonitride formers (precipitates that enhance high temperature performance) and tempering conditions.

At the same time, this new family of steels should acquire all advantages of EUROFER97 in terms of production cost, chemical compatibility, manufacturability, weldability and other assets. It is important to highlight that the current production of the new family of steels attains batches of ~100kg, while the upscaling has been already addressed proving the good potential. The Research addressing irradiation resistance of this new family of steels is currently undergoing and the first results will be available in 2024.

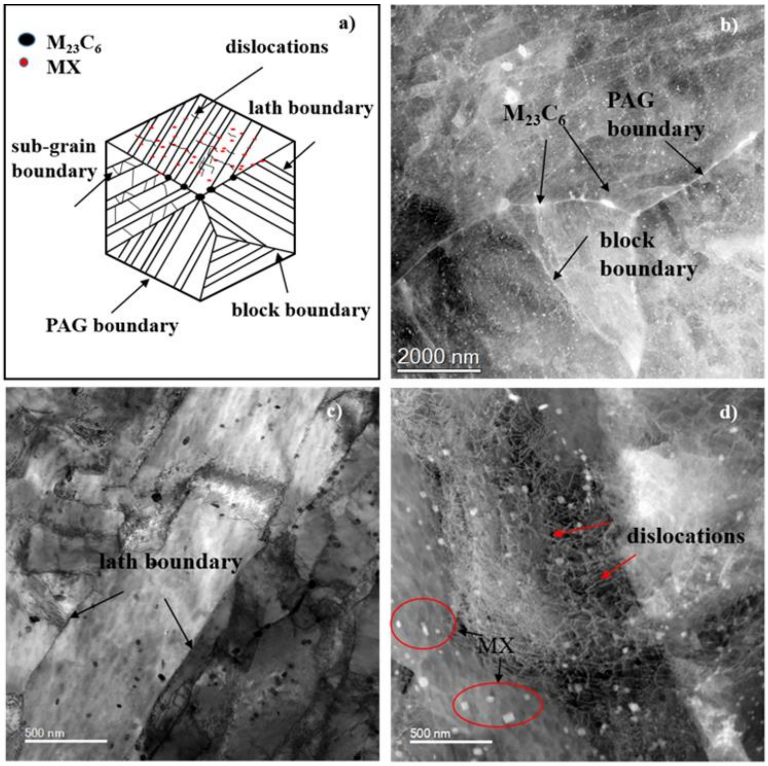

Fig.3. The desired microstructure to achieve high-strength RAFM steel, which was realized in this project.

EUROfusion

TECHNOLOGY TRANSFER PROGRAMME

New affordable and tunable low-activation steel grades for structural materials applications

The Belgian Nuclear Research Centre SCK CEN developed a family of affordable low-activation steel grades that demonstrates superior properties to EUROFER97 (reference material in Europe for plasma-facing components in fusion applications). Its larger ductile range, higher strength and higher creep resistance offer a strong alternative/upgrade to EUROFER97 and can be applied in other applications for components requiring very high ductility (i.e. pipes) or very high strength (i.e. supporting plate/stiffening boards). The material's thermo-responsive traits allow post-production property adjustments, broadening its utility. In extreme heat scenarios, its microstructure changes predictably, beneficial for safety-critical structural assessments.

Innovation and advantages of the offer

The Technology applied for the manufacturing of these new family of steels engages a combination of thermodynamics theory, mechanical treatment and chemical touch that altogether enhances the properties of the EUROFER97 specification steel. Thanks to the mentioned treatment, it is possible to manage the precipitation towards a state favoring high temperature strength without alternating low temperature ductility and toughness. The detailed microstructural investigation proves the proposition coming from the theory, while parametric thermo-mechanical heat treatment enables to extract the most balanced end properties. As a result, the new family of steels adds strong value as structural material in a wide temperature range and covering the neutron loads in much larger amounts than what is envisaged for the currently operating reactors.

Non-fusion Applications

The current domain of Applications covers ITER/CFETR/DEMO/STEP structural material portfolio. The core application is for so called “in-vessel” components where the neutron load and accordingly lattice damage is extensive. The developed family of steels, thanks to a capability to tailor strength/ductility balance, can be perfectly applied in other applications outside fusion for components requiring very high ductility (i.e. pipes) or very high strength (i.e. supporting plate/stiffening boards). Moreover, the properties of the material can be altered by dedicated heat treatment even once the component is produced, which opens another application range. And finally, the overheating of the material, assuming accident scenario, would incur controllable changes in the microstructure and related mechanical properties, which is also of important advantage in assessing the beyond-incident scenario for structural analysis of safety sensitive components.

EUROfusion Heritage

In the 1990s, the European Fusion R&D program started exploring a new reduced activation (9%-Cr-1W-V-Ta) steel for plasma-facing components in nuclear fusion technology. 25 years later, an enormous amount of time and efforts has been conducted characterizing this material and exploring the opportunities to improve. The new materials presented in this paper were originally developed as substitute/upgrade of EUROFER97 steel for the structural applications in DEMO. Advanced steels for helium cooled design concepts of future DEMO reactor, which allow higher thermal efficiency of the fusion power plants, should be able to operate at temperatures up to 650°C on the one hand. The attempt to improve the strength and at the same time to reduce the nil-ductility temperature was made by applying an intermediate cold-working step by quenching & rolling, coupled with a specific chemical alternation (minor alloying elements and variable carbon-nitrogen content).

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.