SMART Materials for high-temperature application in energy systems

Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) are under development for a fusion power plant. SMART Materials can adjust their properties depending on conditions: acting as a sputter-resistant plasma-facing material during plasma operation and suppressing the sublimation of radioactive tungsten oxide during an accident at temperature of up to 1000oC. Qualification of SMART materials under operational and accident conditions is completed. SMART can be prospective materials toward non-fusion applications under an extreme environment for future renewable energy sources: concentrated solar power receivers and high-temperature infrastructure components, such as modern heat-exchangers.

Description of the technology

The Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) materials are under development to address extremely high plasma particle fluence, intensive neutron irradiation and heat loads that will face plasma-facing components in the future fusion power plant. Self-passivating systems introduced for tungsten by Koch and Bolt are aimed at accommodating their properties to the current environmental conditions. During the regular plasma operation, plasma ions and neutrals of high energy may sputter the surface of the smart alloy. The preferential sputtering will first remove the lighter candidate alloying elements: titanium (Ti), chromium (Cr) and yttrium (Y) from the plasma-exposed surface thus providing almost pure tungsten surface facing the plasma. In case of an accident, the alloying elements remaining in the bulk of the smart alloy system will form their own dense oxides, protecting tungsten from sublimation.

Previous research was performed with several binary and ternary alloy system using silicon (Si), chromium and titanium as alloying elements. The W–Cr–Ti system was shown to have the longest and the most effective suppression of tungsten oxidation among all studied alloy systems. At the same time, an addition of yttrium (Y) was proven to have an extremely positive effect on the stability and oxidation resistance of the stainless steels. Based on available experience with steel optimization and taking into account the proven advantages of Y summarized in it was decided to focus efforts on studies of Y-containing smart alloys.

Studies performed on thin W-Cr-Y films demonstrated an impressive oxidation resistance by far outperforming both Ti- and Si-containing alloys and pure tungsten. The thin films featured a remarkable 10.000-fold suppression of oxidation at 1000oC as compared to that of pure tungsten.

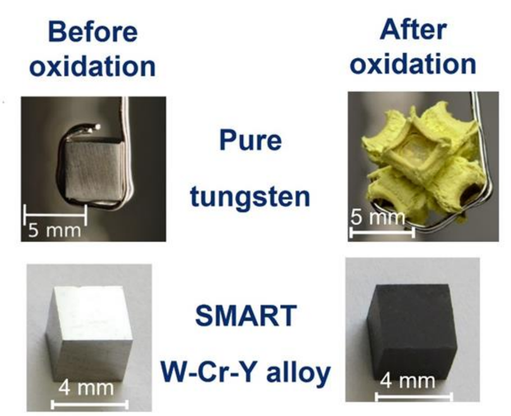

Figure 1: Studies performed on thin W-Cr-Y films demonstrated an impressive oxidation resistance by far outperforming both Ti- and Si-containing alloys and pure tungsten. The thin films featured a remarkable 10.000-fold suppression of oxidation at 1000oC as compared to that of pure tungsten.

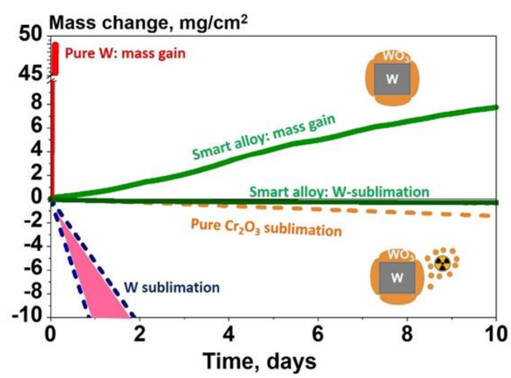

Figure 2: The evolution of the mass change: due oxidation (mass gain) and sublimation (mass loss) depending on exposure time of the SMART alloys, pure tungsten and chromia (Cr2O3).

SMART Materials for high-temperature application in energy systems

Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) are under development for a fusion power plant. SMART Materials can adjust their properties depending on conditions: acting as a sputter-resistant plasma-facing material during plasma operation and suppressing the sublimation of radioactive tungsten oxide during an accident at temperature of up to 1000oC. Qualification of SMART materials under operational and accident conditions is completed. SMART can be prospective materials toward non-fusion applications under an extreme environment for future renewable energy sources: concentrated solar power receivers and high-temperature infrastructure components, such as modern heat-exchangers.

Description of the technology

Following the success of the thin films, bulk SMART W-Cr-Y materials are realized using the mechanical alloying (MA) allowing the solid solution of tungsten and chromium at room temperature. The MA is followed by the state-of-the-art field-assisted sintering technology (FAST). The entire sintering during FAST does not take longer than a half an hour. Fully densified (density >98.6%) samples with the pre-defined microstructure are being obtained in a routine basis.

Presently, principal qualification of SMART materials is completed. Bulk SMART materials demonstrated the identical sputtering resistance to that of pure tungsten being exposed to deuterium plasma to the fluence equivalent to 20 days of continuous operation of the fusion power plant. Direct measurements of tungsten sublimation, pioneered at FZJ, demonstrated at least 40-fold suppression of tungsten sublimation from SMART material.

Following the qualification, the industrial scale-up of SMART technology has been started recently. The industrial scale-up contains both steps of SMART production, MA at industrial partner and sintering using the industrial FAST equipment. First bulk samples produced using solely industrial equipment, became available. At the same time, tuning of industrial technology is required in order to demonstrate the viability of SMART materials at industrial scale.

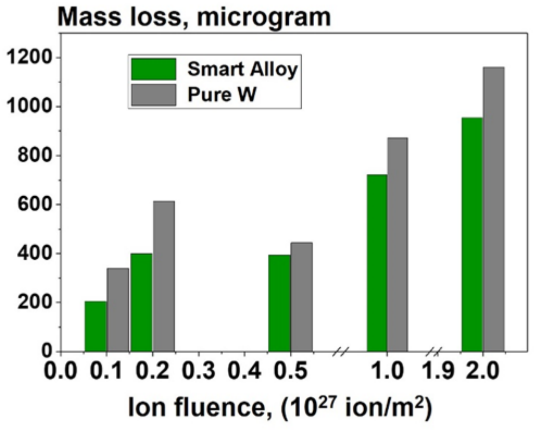

Figure 3: Mass loss due to sputtering erosion of SMART alloys and pure tungsten as a function of plasma fluence.

Figure 4: A large-scale bulk SMART alloy sample sintered using the industrial FAST facility.

EUROfusion
TECHNOLOGY TRANSFER PROGRAMME

SMART Materials for high-temperature application in energy systems

Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) are under development for a fusion power plant. SMART Materials can adjust their properties depending on conditions: acting as a sputter-resistant plasma-facing material during plasma operation and suppressing the sublimation of radioactive tungsten oxide during an accident at temperature of up to 1000oC. Qualification of SMART materials under operational and accident conditions is completed. SMART can be prospective materials toward non-fusion applications under an extreme environment for future renewable energy sources: concentrated solar power receivers and high-temperature infrastructure components, such as modern heat-exchangers.

Innovation and advantages of the offer

- Thin film SMART systems featuring a remarkable 10.000-fold suppression of mass increase due to an oxidation as compared to that of pure tungsten at 1000 °C.
- Bulk SMART materials are manufactured using mechanical alloying and state-of-the-art field-assisted sintering technology (FAST).
- The entire sintering process mechanically alloyed powder does not take longer than half an hour, whereas the sole sintering takes 8 minutes only. This must be compared with the conventional sintering using hot isostatic pressing and taking at least two hours of time.
- Bulk SMART systems featuring the density exceeding 98.6%, confirm the sputtering resistance identical to that of pure tungsten in the course of plasma exposure with the fluence up to 2x1027 ion/cm2, corresponding to 20 days of continuous plasma operation of the fusion power plant.
- Direct measurements of sublimation have been pioneered at Forschungszentrum Jülich, using the custom-made equipment to the existing thermogravimetry facility
- Bulk SMART materials feature at least 40-fold suppression of tungsten sublimation in humid atmosphere with 70 rel.% of humidity and the material temperature of 1000oC.
- Industrial scale-up of SMART alloy technology has been started successfully with the support of EUROfusion WP MAT work package.
- Mechanical alloying at industrial partner takes 21 hours as compared to 60 hours in the laboratory. Each milling batch contains minimum four kilograms of alloyed powder per milling. Extension to hundreds of kilograms is possible, but not tested yet.
- Bulk samples with linear dimensions of 0.5x10x10 cm have been sintered successfully using the industrial FAST sintering facility. The dimensions of samples suit any kind of prospective plasma-facing application in the fusion power plant. Yet, the density of SMART samples produced at industrial scale is slightly below 90%. The fully automatic industrial sintering routine of SMART materials was developed and tested successfully.
- In the new SMART samples, the source W and Cr powder from industrial supplies were used. These, at the price of about 60 Euro/kg and 56 Euro/kg (in prices of June 2021) are highly competitive to pure tungsten. Related to the pure tungsten component, fewer mass of W-Cr-Y is needed – due to slightly lower density of the SMART. Therefore, the technology has a potential of superseding of pure tungsten in cost efficiency. At the same time, yttrium still bought at a laboratory supplier company at the price of 10.000 Euro/kg is extremely expensive. Effort must be taken on finding the industrially-available yttrium.

Non-fusion Applications

Concentrated Solar Power stations (CSP) are potentially the most effective way to transfer solar energy to electricity. However, due to lack of suitable high-temperature materials the full potential of solar¬-thermic plant technology has not been realised yet. The solar-driven processes of combined gas and steam turbines are the most effective CSP technologies so far, but they require operating at temperatures higher than 900°C.

High-temperature heat exchangers may be required for several energy systems. Here, SMART materials could make an important, if not decisive contribution in novel energy systems.

EUROfusion Heritage

Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) are under development for the primary application as plasma-facing materials for the first wall in a fusion DEMOnstration power plant (DEMO). Plasma-facing components will be exposed to extremely high plasma particle fluence, intensive neutron irradiation and heat loads exceeding those in any existing fusion experiment by orders of magnitude. Conventional materials will unlikely be able to accommodate the envisaged loads and fluxes simultaneously Newadvanced plasma-facing materials have to be developed for the fusion power plant application. Part of this work has been carried out within the framework of the EUROFusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant Agreement No. 633053.

Litnovsky, A.; Klein, F.; Tan, X.; Ertmer, J.; Coenen, J.W.; Linsmeier, C.; Gonzalez-Julian, J.; Bram, M.; Povstugar, I.; Morgan, T.; et al. Advanced Self-Passivating Alloys for an Application under Extreme Conditions. Metals 2021, 11, 1255. https://doi.org/10.3390/met11081255

Visit our website to learn how fusion can help your business
www.tech-transfer.eurofusion.eu

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.