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# SMART materials for DEMO: Towards industrial production

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ABSTRACT

Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) are under development for a fusion power plant. SMART exhibits similar sputtering resistance as that of pure tungsten during regular plasma operation. Under accident conditions, SMART demonstrates the suppression of oxidation – a remarkable advantage over pure tungsten. The viability of SMART technology has been shown on a laboratory scale.

Presently, the industrial scale-up of SMART technology is underway. This activity comprises the industrially supplied feedstock materials for SMART, mechanical alloying of powder at industry and sintering of SMART materials using industrial equipment. Industrial mechanical alloying can be accomplished within 21,5 h of milling, providing at least four kilograms of fully alloyed powder. Rectangular industrial SMART samples feature linear dimensions of 10 cm, a thickness of 0.5 cm, a weight slightly below 1 kg and a relative density exceeding 97 %.

The transition to industrial feedstock suppliers allowed SMART to outperform pure tungsten in powder procurement costs needed for plasma-facing components. The status of industrial SMART technology is given along with an outlook on future activities.

## 1. Introduction and motivation

Safety of a fusion power will play a decisive role in several aspects, including the public acceptance of fusion power as an attractive energy source. Safety operation will also provide a crucial input to the licensing of the fusion power plant [1]. Passive safety measures represent an attractive option for contributing to an overall safety concept. Among others, a development of advanced materials [2–4] is aimed at ensuring the "built-in" safety measures.

Presently, due to number of advantages including high resistance to melting and low sputtering yield by plasma particles, low tritium retention, benign activation and high thermal conductivity at elevated temperatures, tungsten is chosen as a baseline plasma-facing material for the DEMOnstration fusion power plant (DEMO) [5]. However, in case of a severe accident such as e.g. earthquake destroying the vacuum vessel of the power plant, tungsten plasma-facing components will be subject to air ingress into the vacuum vessel. In the absence of an active cooling due to e.g. broken cooling piping system during the accident, the temperature of the tungsten plasma-facing armor will rise due to volumetric nuclear decay heat. Extensive modeling [6] was performed within in the European Fusion Development Agreement (EFDA) framework. Among others, the response of tungsten armor during a severe accident was modeled. Results of this study evidence the extreme heating of the tungsten armor to temperatures of 1000 °C and above. Tungsten will experience the impact of these extreme temperatures for several weeks. Under elevated temperatures tungsten oxidizes, which subsequently leads to the sublimation of the neutron-irradiated radioactive tungsten oxide $WO_3$ to an atmosphere. The assessment [7] provides the sublimation rates for 1000 $m^2$ total area of the tungsten first wall armor ranging between 10 and 100 kg of tungsten oxide per hour. In addition, the oxides of radioactive elements created during tungsten irradiation by fusion neutrons, such as rhenium and osmium [8,9] will be mobilized into the atmosphere.

The tungsten-based Self-passivating Metal Alloys with Reduced Thermo-oxidation (SMART) may provide an effective response to such a safety challenge imposed by a severe accident. The self-passivating

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materials initially proposed by Koch and Bolt [10] are under development in several European [7,11–28] and international laboratories [29–34]. SMART materials adapt their properties to the environment. During the regular plasma-operation, plasma particles will sputter the lighter alloying elements, leaving the pure W surface facing the plasma. The formed nearly pure tungsten surface experiences the least sputtering damage due to lack of energy of incident particles. Under regular plasma operation the tungsten layer will protect the underlying alloying elements from sputtering. During the accident, alloying elements will diffuse from the bulk to the surface of the material, "re-filling" the depleted part of the material and creating their own protective oxide scale on the surface of SMART. Such a protective scale will effectively prevent tungsten from oxidation and subsequent sublimation into the atmosphere.

The most efficient SMART materials contain tungsten as the base matrix element, chromium (Cr) as a passivating element and yttrium (Y) as the so-called active element, being added to an alloy in small amounts, typically 1–5 at.% and significantly increasing oxidation resistance [35,36]. Different laboratories have presented their own W-Cr-Y systems. The content of alloying elements varies only a little in all materials under study [7,12,16,17,22,25,37]. The SMART materials developed at Forschungszentrum Jülich GmbH, Germany (FZJ) contain the 11.4 wt.% of Cr, 0.6 wt.% of Y and tungsten matrix constituting the rest.

Bulk SMART materials are produced using mechanical alloying (MA) of elementary W, Cr and Y powders. Overviews of mechanical alloying are provided in [12,26]. The W-Cr solid solution is formed with Y-containing nano-particles. Then, it is sintered to the bulk materials using among others, the Field – Assisted Sintering Technology (FAST). During sintering, in addition to high temperatures and pressures, electric current is flowing through the sample thus allowing for a very fast sintering result. The shortest sintering time for SMART is presently about 7 min.

Bulk SMART materials have already demonstrated an impressive performance under fusion power plant relevant conditions. A series of plasma exposures have been performed in the European linear plasma facilities PSI-2 in Jülich, Germany and in MAGNUM PSI, Eindhoven, The Netherlands. For a comparative study SMART material and pure tungsten samples were subjected to the impact of deuterium stationary plasma. Materials were heated to temperatures up to 650 °C, corresponding to the first wall armor temperature in DEMO [38]. In all studies energy of impinging deuterium ions was kept at about 120 eV, providing a conservative approach to sputtering of the first wall armor. The results of the study are provided in [19,39] An overview of results can be found in [27]. Both pure tungsten and SMART materials demonstrated identical sputtering resistance at the plasma fluence corresponding to 21 days of the continuous DEMO operation. The formation of the protective tungsten layer was evidenced experimentally.

The oxidation resistance of SMART materials is outstanding. The samples were exposed at the pressure of 100 kPa and a temperature of 1000 °C to a humid atmosphere containing 70 vol.% of humidity at 25 °C. These conditions were aimed at attaining the best reproduction of a severe accident in the fusion power plant addressed by modeling [6]. The corresponding results were reported in [24,27]. An impressive oxidation resistance, exceeding a $10^4$-fold of that of pure tungsten was measured. The direct measurements of tungsten sublimation were pioneered at FZJ. These studies show more than 40-fold suppression of tungsten sublimation from the SMART material compared to the sublimation from the pure tungsten sample. The suppression of tungsten oxidation persists under described conditions for a timespan of at least three weeks, warranting passive safety for the power plant during the accident.

Fundamental studies aimed at understanding SMART system at a nanoscale have progressed well in the recent years. Among others, the state-of-the-art experiments coupled with extensive first-principles modeling revealed a critical role of yttrium in the overall performance of SMART. Despite its low content in the material, yttrium cleans the grain boundaries by binding oxygen. It even shifts the temperature boundary of binary solid W-Cr solution, stabilizing the W-Cr binaries at about 300 °C lower temperature [27,40].

Following the successful feasibility studies during the regular plasma operation as well as under accident conditions, efforts were focused on scale-up of the SMART technology to an industrial scale. This paper describes the present status of the scale-up.

### 1.1. Mechanical alloying at an industrial scale

Mechanical alloying (MA) is the first step in production of SMART materials. Having performed an extensive study on MA [26] it was decided to pursue the way of the high-energy ball milling at an industrial level. The unique expertise in this area belongs to the Zoz GmbH company. The company possesses vast experience in MA along with a line-up of their own designed and patented machines for MA.

The joint effort of FZJ and Zoz GmbH has been started in 2020. The entire process is presented in Fig. 1. The elementary pre-weighted W, Cr and Y powders are supplied to Zoz GmbH in bottle-like containers, and subsequently are mixed in the mixing bottle, Fig. 1a. Afterwards, the bottle is mounted on top of the Simoloyer® mechanical alloying facility [41], Fig. 1b. The powder mixture from the mixing bottle is disposed into the drum-like interior of the Simoloyer, Fig. 1b. The Simoloyer family of MA mills possesses the steel interior of the milling vessel and the steel milling rotor, Fig. 1c and 1d, with leading blades made from Stellite, the low-wear Cr-cobalt (Co)-based alloy. The mechanical alloying at Zoz GmbH is performed at the cylinder-rotor geometry – in contrast to the MA at the laboratory scale in FZJ, where the planetary ball milling was undertaken.

During the alloying at the industrial partner, the powder samples are taken regularly for the post-milling evaluation. The sample containers are shown in Fig. 1e. Samples of powders are taken under argon atmosphere to suppress the undesirable oxidation. The evaluation of sample powders comprises the study of the degree of alloying using the X-ray diffraction spectroscopy (XRD), elemental analysis of impurity uptake into alloyed material using the inductively coupled plasma, optical emission spectroscopy (ICP OES) at FZJ along with the burn product emission spectroscopy at the external contract partner. In total, more than 50 different elements are monitored regularly using the aforementioned techniques for each powder sample.

The first attempt to perform MA at Zoz GmbH was undertaken in late 2020. Here the Simoloyer® CM 20 facility filled with steel balls – the standard milling setup - was used. Use of the tungsten carbide milling tools and balls pursued at laboratory scale was found to be impossible in the industry due to economic and extensive wear considerations. This was another significant difference to the established lab research MA

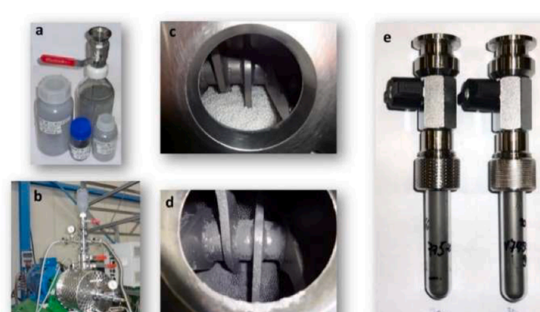


**Fig. 1.** Details of the mechanical alloying at industrial scale: a) bottles with elemental W, Cr and Y powders from FZJ and the mixing bottle from Zoz, b) mixing bottle attached to the Simoloyer® CM 20 industrial mill, c) a view to the interior of the Simoloyer® CM 20 mill before the milling and d) after 90 min of the milling and e) sample powders taken under argon atmosphere from the Simoloyer® CM 20 mill.

technique described in [22]. The minimum amount of the alloyed powder procured by an industrial partner is 4 kg, compared to about 100 g of powder available after lab scale MA. The scaling-up the production of alloyed powders to the levels of hundreds of kilograms at the moment looks relatively straightforward with the Simoloyer machine line. In contrast to continuous planetary milling at a constant rotation speed in laboratory conditions, the standard milling in Simoloyer was performed in a cyclic manner. In each cycle, a high intensity milling at 450 rotations per minute (rpm) for 45 s was followed by lower intensity milling at 200 rpm for 15 s.

During mechanical alloying at the industrial partner, particular attention was given to the iron content in the alloyed powder. Iron is known for its affinity to oxygen leading to the formation of a variety of iron oxides [42]. The presence of iron impurity in industrial SMART powder would inevitably lead to degradation of oxidation resistance. Despite the use of steel interior and balls, the resulting iron content in the alloyed powder was found to be moderate, not exceeding 3 wt.%. The complete alloying was attained after 21.5 h of milling, as compared to 60 h needed in the laboratory. Nevertheless, it was decided to perform the further optimization of MA at the industrial partner aiming at further suppression of parasitic impurities in the alloyed powders. As the economically advantageous alternative to tungsten carbide usually used in laboratory research, the yttrium-stabilized zirconia balls were used in subsequent optimization campaigns in 2021 - 2023.

The pilot milling campaign (MA 2021) using zirconia balls was performed in 2021. Unlike the clearly detrimental effect of iron impurity, the effect of possible zirconium uptake into the SMART powder is not fully predictable. On one hand, the zirconium reacts with hydrogenic species and forms hydrides [43] – a clearly alarming feature in fusion environment. On the other hand, the addition of Zr has resulted in even better oxidation performance of the lab scale W-Cr-Y-Zr systems [44]. For the sake of predictability of the performance of industrial SMART it was decided to try keeping the zirconium content in industrial SMART at the lowest level attainable.

The impurity uptake of iron and zirconium is presented in Fig. 2a and 2b respectively. As can be seen from the figure, the introduction of zirconia milling balls has successfully solved the issue of the iron uptake in MA 2021 already. The change to zirconia balls has led to a more than 35-fold decrease in iron content from 3.00 wt.% down to 0.08 wt.%.

Yet, the significant uptake of Zr, Fig. 2b was noticed during this milling, calling for further optimization of the MA scenario at Zoz GmbH. Four optimization campaigns were undertaken aiming at tuning the milling procedure and reducing the zirconium uptake.

The milling campaign MA 1 2022 was undertaken to see the effect of the alloying of milling balls and the interior of Simoloyer on impurity uptake. A gradual alloying of milling tools is a known effect, leading to the reduction of impurities in final powders. MA 1, however, did evidence an opposite result: no Zr reduction was attained, whereas the Zr content was generally even higher than that during the pilot milling campaign 2021, Fig. 2b. Iron content was stabilized at similar levels as in the pilot campaign 2021, Fig. 2a. In MA 1, the complete alloying was

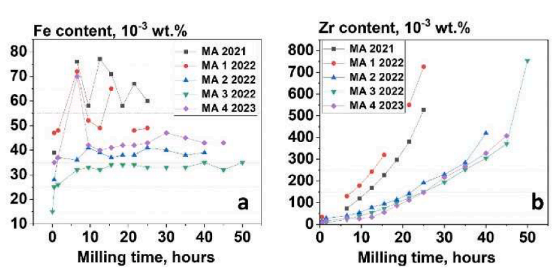


**Fig. 2.** The evolution of impurity content of a) iron and b) zirconium during mechanical alloying at industrial scale. The results of the pilot mechanical alloying campaign in 2021 (MA 2021) are plotted with data from four optimization campaigns: MA 1, MA 2 and MA 3 and MA 4.

attained after 25 h of milling.

For subsequent campaigns MA 2 – MA 4 it was decided to use the "milder" milling conditions. During the longest cycle of 45 s, the rotating speed was reduced to 315 rpm. The aim was to combine the full alloying with a reduced wear of zirconia tools. To compensate for a lower milling intensity, an increase in milling time up to 50 h was realized in this study.

In MA 2, new zirconia milling balls were used. A significant reduction of Zr content to 0.4 wt.% after 40 h milling can be witnessed during the "milder" milling in MA 2 as compared e.g. to MA 1. The results are presented in Fig. 2b.

The MA 3 campaign has been made to investigate whether the stationary milling conditions without the undesirable wear of the milling tolls are attained. MA 3 was performed therefore, with the same milling parameters for a "milder" milling using the old milling balls from MA 2. The MA 3 featured in general, identical results as the MA 2. At the same time, during the last 5 h of milling i.e. from 45 to 50 h, the Zr content has increased from 0.4 wt.% to nearly 0.7 wt.%, outlining the potential risk of the wear of milling tools. At the same time, it was noticed that extending the milling duration from 45 to 50 h does not result in any positive effect.

The campaign MA 4 was aimed at investigating if the wear has occurred during MA 3. Old milling balls from MA 2 and 3 were used in MA 4. The total milling time was again reduced to 45 h. The Zirconia content grew gradually up to 0.4 wt.% in agreement with the results of MA 2, Fig. 2b. In the beginning of MA 4 the Zr content starts to increase from nearly zero concentration level. This observation evidences the absence of measurable wear caused by the preceding campaign MA 3.

It should also be noted that iron content in the powder was further decreased during all three campaigns with a "milder" milling, reaching 0.04 wt.%, Fig. 2a. MA 2–4 results evidence an almost 75-fold decrease in the iron content attained by using Zirconia milling balls.

### *1.2. Industrial sintering of SMART materials*

As soon as the first industrially alloyed powders became available, the following step in the scale-up was undertaken. The Forschungszentrum Jülich GmbH possesses its own industrial facility Dr. Fritsch DSP 515. The first powders from Zoz GmbH were sintered in Jülich using the above-mentioned industrial facility. To the knowledge of the authors, the rectangular sintering dye was applied for the first time for fusion applications. Using the rectangular sintering sample potentially provides the decisive advantage of a minimum material loss as compared to conventional cylindrical material samples produced using hot isostatic pressing and FAST of other producers.

The first rectangular sample was sintered successfully. This sample with the weight of 750 g was presented in [27]. However, the density of industrially produced material relative to theoretical density of SMART was about 70 % only. In addition, the powder losses due to the poor isolation of the sintering tools were about 50 g.

At the same time, the facility got stuck several times during the sintering showing the immaturity of the first sintering program.

Therefore, significant efforts were made on further optimization of FAST technology for industrial SMART production. At Forschungszentrum Jülich, these efforts have comprised the deep learning of the industrial facility, understanding the algorithms of decision-making during sintering and improved programming.

At the same time, the joint research and development activity with industrial producer Dr. Fritsch GmbH has been started. This activity has rapidly grown into a very efficient collaboration program. The FZJ specialists were given the opportunity to perform the sintering tests in DSP 615 FAST facility (Fig. 3a) at Dr. Fritsch company. The updated program was transferred from FZJ to Dr. Fritsch. The sintering was performed in a fully automatic mode without any interruption by an operator.

Sintering scenarios, specifically tuned to the industrially alloyed


**Fig. 3.** Field-assisted sintering technology of SMART materials at industrial scale: a) sintering of SMART sample in DSP 615 facility at Dr. Fritsch GmbH from the powder produced by Zoz GmbH and b) the rectangular SMART sample produced at FZJ, using the industrial FAST facility Dr. Fritsch DSP 515 using know-how of Dr. Fritsch, powder from Zoz GmbH, programming from FZJ. The sample features a relative density which exceeds 97 %.

powders were developed. The detailed description of scenarios and results is the subject of a dedicated paper and will be published elsewhere. As compared to the standard FAST sintering scenario provided in [16, 22], the following changes were used for sintering the bulk industrial SMART materials:

1. The final sintering temperature was increased from 1460 °C to 1500 °C.
2. The holding time at 1500 °C for 10 min was introduced.
3. The pressing of the sample at 50 MPa during the cooling phase for about 6 min was introduced.

The temperature ramp of 200 °C/min remained the same in both industrial and laboratory sintering scenarios.

During the first sintering at Dr. Fritsch GmbH, the specialists of the company supervised the sintering process, sharing their mostly unique knowledge. The sample sintered at Dr. Fritsch has attained a relative density exceeding 90 %, which is more than a 25 % improvement within less than a year of R&D.

Furthermore, the collaboration with Dr. Fritsch resulted in the transfer of unique know-how to FZJ. The list of improvements presently used for sintering of industrial SMART currently comprises:

1. A novel 4-segment sintering tool from Dr. Fritsch.
2. A unique powder leveling tool from Dr. Fritsch.
3. The use of carbon-based colloidal glue to minimize the powder losses during sintering.
4. As described above, a new program from FZJ for a fully automatic sintering and a new sintering scenario.

As a result, the newest rectangular SMART sample, Fig. 3b revealed a relative density exceeding 97 % with nearly zero loss of powder: 3 out of 791 g. These attained parameters represent the remarkable result of the joint research and development program on industrial sintering.

It was decided that the further efforts of both partners will comprise the R&D on sintering both in Jülich and in Fellbach using both DSP 515 and DSP 615 facilities, featuring improved temperature control and possibly, even automatic dispensing of the powder and automatic batch handling of sintered samples in future.

### *1.3. Procuring industrial feedstock and closing the fully industrial production cycle*

In the frame of the industrial scale-up, the accompanying research was undertaken at the lab scale facilities at FZJ aiming at substituting the feedstock powders previously delivered by the scientific suppliers with the ones from industrial suppliers. This activity was found to be necessary to provide competitive costs for SMART materials in future. The use of less expensive and usually, less pure industrial powders could have led to new and detrimental effects in the performance of SMART materials. The step-by-step introduction of industrial powders have been started in 2019. First, tungsten powder from industry supplier was introduced. The transfer to the industrially procured chromium powder followed in 2021.

The industry procured the two main feedstock components of SMART materials: tungsten and chromium powders, by the end of 2021. This change allowed making simple calculations of the feedstock material need and the accompanying costs for the first wall armor of DEMO-size reactor with the 1000 $m^2$ total surface of the first wall. The results of these calculations are provided in Table 1.

The entire 3 mm thick first wall armor made out from pure tungsten would weight 60 tons. The total price for such an armor in 2021 euros would be of order of 3.6 million euros. Here, the purchase orders available at FZJ were used for price estimates.

Due to the smaller total density, even a fully densified SMART first wall of the same thickness and area will require less material i.e. 46 tons. Yet, the total price of the feedstock material for the first wall was higher than that of pure tungsten FW: 5.4 million euros.

Analyses of cost composition demonstrated that the main contribution to the total cost was provided by a scientific supplier of yttrium: from 5.8 million euros, at least 2.8 million were due to yttrium procurement.

Finally, an industrial supplier of yttrium was found. As expected, the price of industrial yttrium was more than 5-fold lower than that for lab research. The final calculation has yielded the feedstock price of the SMART material of 3.3 million euros. The SMART first wall represents in fact, more economically viable solution. No production costs were included in the above estimates.

Generally, it should be noted that the power plant building costs will be exceeding those for the material of the first wall armor by a great margin. Here, fusion facilities are not yet able to provide a good merit of the estimate – since there is no working fusion power plant available yet. However, experience with controlled fission might be helpful in such a respect. The report [45] represents quite an extensive study of the cost factors for the fission reactors of generation IV. According to [45], the average power plant construction costs vary between 0.8 billion and 3.4 billion US dollars. Using the similar number as a figure of merit, we can conclude that the procurement of the first wall feedstock material, whether a pure tungsten or SMART material, will represent a minor fraction only of the total cost needed for construction of a fusion power plant.

**Table 1**
The calculation of the feedstock material price for the first wall (FW) of DEMO fusion power plant.

| Feedstock material | Amount required | Total feedstock price |
|---|---|---|
| Pure W (industry) | 60 tons | 3.6 million euros (2021) |
| SMART: W (industry) +Cr (industry) + *Y* (lab research supplier) | 46 tons | 5.8 million euros (2021), where Y costs 2.8 million euros |
| SMART: W+Cr+Y (all industry) | 46 tons | 3.3 million euros (2022) |

### 1.4. Summary and outlook

SMART materials – the self-passivating tungsten alloys are developed as a passive safety measure for the future fusion power plant, such as DEMO. The SMART materials feature plasma compatibility similar to that of pure tungsten in conditions, corresponding to regular DEMO plasma operation. Under accident conditions comprising the loss-of-coolant event and air ingress, the SMART materials create the chromia protective scale, suppressing tungsten sublimation into the atmosphere. SMART technology has already demonstrated its viability both under regular plasma conditions and in the experimentally reproduced severe accident.

Following the successful feasibility studies, most of research and development is now focused on industrial scale-up of SMART technology. Mechanical alloying at industrial partner demonstrated the capability to produce at least 4 kilogram of fully alloyed SMART powder after 21.5 h of milling (aggressive milling) and after 40 h in case of milder, low-wear milling with a less impurity uptake. Therefore, low-wear milling is presently a preferred option.

Industrial scale-up of sintering technology led to the production of SMART samples of rectangular shape, the linear dimensions of 10 × 10 cm, thickness of 0.5 cm and a relative density of at least 97 %.

Finally, the procurement of feedstock source W, Cr and Y powders from industrial suppliers only, has completed the industrial production cycle of SMART materials. The rough estimate of procurement costs revealed also the decisive economic attractiveness of SMART as compared to that of pure tungsten.

Nevertheless, several open questions remain to be solved on the way of establishing the fully operational and optimized industrial scale-up. In terms of mechanical alloying, further tuning of alloying scenarios is required. The ultimate goal of this tuning is to reduce parasitic impurities in the powder, such as zirconium, carbon, oxygen, and others. The complete suppression of some impurities, such as Zr is believed to be impossible due to the nature of manufacturing process.

Several open questions are still to be addressed during sintering at the industrial scale. Among those questions is the capability of a direct measurement of the sintering current. Importance of such measurements was outlined in [33]. Another important aspect is better temperature control over the sample during sintering. Both current density and temperature distributions are of crucial importance for reproducible and optimized sintering of the fully densified samples. An important topic is also the improved flowability of the SMART powder. This factor is believed to play an important role in the subsequent full automatization of the sintering process via automatic dispensing of SMART powder into the sintering dye. Alternatively, the SMART powder with good flowability may open the way for alternative production route of the SMART-based plasma – facing components using e.g. low-pressure plasma spraying technology, as applied in [46].

The microstructure of the best densified industrial SMART needs to be studied In future. These studies should be followed by the qualification of oxidation resistance of industrially produced alloys. In particular, the effect of Zr on oxidation performance must be investigated. Subsequently, mechanical qualification of industrially produced SMART must be performed. Investigations of self-passivating alloys produced at laboratory scale demonstrate a little effect of neutron irradiation on their microstructure and mechanical properties [47]. Irradiation of industrially produced SMART will provide an important input in the final material qualification for DEMO.

Certainly, the realization of the industrially dense high-performance SMART bulk materials is not a final destination in the production route of SMART. Design, production and testing of the SMART – based plasma-facing components should finalize the maturity of SMART technology. Joining SMART and structural materials such as RAFM steels by e.g., brazing [34] or direct sintering [48] can be challenging and therefore, represents another topic of crucial importance.

## CRediT authorship contribution statement

**Andrey Litnovsky:** Writing – review & editing, Writing – original draft, Resources, Project administration, Conceptualization. **Jie Chen:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Martin Bram:** Writing – review & editing, Resources, Methodology. **Jesus Gonzalez-Julian:** Writing – review & editing, Resources. **Henning Zoz:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Hans Ulrich Benz:** Writing – review & editing, Methodology, Investigation. **Jens Huber:** Resources, Validation, Writing – review & editing. **Gerald Pintsuk:** Writing – review & editing, Resources, Funding acquisition. **Jan Willem Coenen:** Writing – review & editing, Supervision. **Christian Linsmeier:** Writing – review & editing, Resources, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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