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# ODS F/M Steels for the Application to SFR Fuel Cladding

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## 1. Backgrounds

The importance of a material development for the future energy systems (Gen IV and fusion reactors) has been rapidly growing for the last decade and expected to be emphasized in the coming years. Several countries including Korea had jointly formed the Gen IV International Forum (GIF) to develop the future nuclear energy systems that can be licensed, constructed, and operated. These systems are to have a considerable increase in safety and be economically competitive when compared with the existed commercial reactors. In particular, the systems should produce a significantly reduced volume of nuclear wastes. From this point of view, sodium-cooled Fast Reactor (SFR) is strongly considered as a future nuclear energy system in Korea.

Although higher operating temperatures are considerably required in order to improve the thermal efficiency of SFR, the upper operating temperature would be limited to 550~600$^{o}$C for the conventional 9Cr-1Mo mod., HT9, F82H, 9Cr-2WVTa, EUROFER and JLF-1 as a fuel cladding. The fuel cladding should thus have superior mechanical properties above 650$^{o}$C. As one of the alternative cladding materials, the oxide dispersion strengthened (ODS) ferritic/martensitic (F/M) steels with superior creep strength above 700$^{o}$C are expected to be prospective materials in these cases. The ODS F/M steels would operate under a higher temperatures than 700$^{o}$C, contacting with alkali liquid, and be radiated by neutrons to as high as 200dpa.

In this study, the current status of ODS F/M steels and the key parameters ultimately to be solved for its application as a cladding materials of SFR fuel were discussed, and the R&D strategy and activities were proposed for the advanced ODS F/M steels.

## 2. R&D Status of ODS F/M Steels

As a cladding material of SFR fuel, F/M steels have become more attractive than austenitic steels due to their higher swelling resistance. However, the mechanical properties of the F/M steels degrade rapidly above 700K. The major driving force behind the development of processing techniques for the ODS alloys has always been the need for better alloys at higher temperatures. The first ODS alloy, "ductile tungsten" was produced in 1910 by a traditional powder metallurgy. The mechanical alloying (MA) process was introduced for producing new ODS alloys in 1970. By the replacement of carbide precipitates with stable oxide dispersoids, their good thermal conductivity, swelling resistance and low irradiation damage accumulation derived from the base material, are further enhanced by the presence of a fine dispersion of oxide particles. Their strength and creep properties are also improved relative to the base material.

The most important factor to select the oxide dispersoid is its stability under high temperature and under irradiation. $Y_2O_3$, $MgAl_2O_4$, MgO and $Al_2O_3$ have relative higher melting points and have good phase stability below 1400°C. The dissolution occurs for all the oxide types and for all the irradiations, but the less unstable oxides are $Y_2O_3$ and $MgAl_2O_4$. Though $MgAl_2O_4$-ODS steels were reported, the ODS F/M steels focus on the $Y_2O_3$-ODS steels. The Cr content of the ODS F/M steel was basically ranged from 9 to 13%. But high-Cr ODS F/M steels up to 20% (e.g., PM2000, MA956, MA956HT) were also studied. Some of W, V, Mn, Mo, Ta, Al and Ni were added for strengthening or corrosion purpose. But Mo, Ni, Al, Ti were undesired elements for low activation for neutron irradiation.

Compared with their base alloys, the ODS alloys showed higher strength and similar or higher elongation at a temperature range from RT to 700°C. The creep rupture strengths of the ODS alloys appeared to be higher than those of their base alloys, and reached about 120 MPa at 700°C for 10,000h. The DBTT had improved to values between −40 and −80 °C, but did not reach the very low DBTT and high USE of base alloys.

The ODS F/M steel had a superior oxidation resistance with almost no dependence on temperature and time up to 1000°C. Compatibility tests of ODS F/M steel with Na and Li liquids and Pb–17Li at temperatures up to 700°C showed higher resistance to corrosion than SS316.

The microstructure of ODS F/M steel was composed of ferritic/martensitic matrix, nano-metric $Y_2O_3$ and/or $Y_2Ti_2O_7$, stringers formed by large second-phase carbide particles, and sometimes pores. The elongated grains presented after a rolling were destroyed by inducing an $\alpha \rightarrow \gamma$ phase transformation in the martensitic steels and a recrystallization in ferritic steels.

After an irradiation of ODS F/M steel, there was the possibility of an oxide particle dissolution. Macroscopic structural changes such as grain growth and/or recovery of the lath boundary were not seen, but $\alpha'$ phase or $\chi$ phases were observed. Void swelling remained below 1.8% even with neutron irradiated up to 205dpa. The increase of the tensile strength and decrease of the elongation are much lesser than those of the conventional steels. And embrittlement happens above 793K but is not significant and the lower shelf energy is still fairly high.

## 3. Key Parameters To Be Solved

*3.1. Anisotropic and fracture toughness*

A rolling process to manufacture claddings leads to an extremely elongated fine grain morphology parallel to the rolling direction, which induces a higher creep rupture strength in this direction due to the large grain aspect ratio. However, a primary stress mode in the cladding of the fission gas pressurized fuel pins is the transverse hoop direction, where a ductility loss and deterioration of the creep rupture strength take place. Thus, creating equiaxed grains is a key technology for realizing the ODS F/M steel cladding.

The DBTT is between +60 and +100 °C for the hipped ODS EUROFER-97. Through thermo-mechanical treatment, it had improved to values between −40 and −80°C. The upper-shelf energy (USE) was increased by about 40%. Nevertheless, ODS F/M steels did not reach the very low DBTT and high USE of EUROFER-97. Tests on 1/3 Charpy-sized three-point bend specimens of hot-extruded ODS-MA957 bar showed that the toughness, the cleavage transition temperature regime, as well as the basic fracture process itself, are highly dependent on the orientation. As-extruded state with a fine grain microstructure presents a very attractive DBTT value (−110 °C) as compared with the recrystallized state (+60°C). However, the recrystallized condition exhibits higher values of the USE level.

*3.2. High-temperature compatibilities*

The compatibilities of ODS F/M steels with liquid Na at 600~700°C up to 10000 h is good. Compatibility tests at higher temperatures than 700°C do not exist and are required on the basis of an accident condition.

*3.3. Irradiation tests*

Up to now, very limited data exists on a neutron irradiation up to 200dpa. And a 200dpa neutron irradiation showed a great variation in swelling between different heats or different heat treatments of the same steel. Mechanical test is only done for about a 20dpa neutron irradiation. But mechanical properties changes under a higher neutron irradiation are needed and the causes should be confirmed.

*3.4. Manufacturing techniques*

Almost all of ODS F/M steels are made through the MA method. The MA powders were compacted by a hot extrusion or HIP. Cold rolling or hot rolling can be used to obtain the final products. Soften heat treatment is necessary between the rolling steps. And a final heat treatment is very important to obtain the expected microstructures and properties. The MA parameters, rolling procedures, and heat treatment conditions should be optimized and better controlled. And appropriate welding method should be found and demonstrated.

## 4. Strategy for Advanced ODS F/M Steel R&D

As an advanced ODS F/M steel R&D, the following steps are necessary: 1) Preliminary manufacturing and testing, 2) Choosing and solving key techniques, 3) Obtaining and demonstration key performances, 4) Demonstration and verification products, and 5) Industrialization.

## 5. Proposed Main R&D Activities

- ✓ Alloying effects
- ✓ Manufacturing effects with thermo-mechanical processes, including anisotrophy and joining
- ✓ High-temperature(>700°C) properties, including mechanical and corrosion performances
- ✓ Irradiation tests with higher neutron dose (>200dpa)
- ✓ Thin tube fabrication (~3600 mm in length)

## 6. Summary

ODS F/M steels are prospective as cladding materials of a SFR fuel. Though current results are encouraging, the ODS F/M steels are far from industrious use as an SFR Fuel. The research targets are to solve the key techniques, to obtain necessary performances, and to manufacture cladding tubes. In order to achieve these goals, main research activities including alloying effects research, process effects research, high-temperature(>700°C) properties research, irradiation tests, and thin tube fabrication are proposed.

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