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Progress in development of China Low Activation Martensitic steel for fusion application

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Abstract

A series of R&D activities on the structural material China Low Activation Martensitic steel (CLAM) and related blanket technology are being carried out in Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). A summary of these activities is presented, mainly covering the composition design, property tests, techniques for HIP joining and coating, and activation analysis. In addition, a nuclear material database FUMDS is introduced, which is under development based on the requirement for CLAM data management.

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1. Introduction

The design activities of Fusion Design Study (FDS) series fusion reactors with liquid LiPb tritium breeder blankets [1–3] have been underway at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) for years, in which China Low Activation Martensitic steel (CLAM) [4] is considered as the primary candidate structural material for the blankets.

As is well-known, reduced activation ferritic/martensitic steels (RAFMs) are presently considered as the primary structural materials for the DEMO fusion plant and the first fusion power reactors because of their attractive properties [5–7]. Research on a new version of RAFMs i.e. CLAM was started five years ago at ASIPP in China based on the results and experience on the other RAFMs, such as EUROFER97, F82H, JLF-1 and ORNL 9Cr-2WVTa, which were widely studied in the world [5–7].

A series of R&D activities on CLAM and related technology for liquid LiPb blankets of FDS series designs are being carried out in ASIPP under wide collaboration with other institutes and universities in China and overseas institutes. This paper presents the status of the activities which mainly cover composition design, smelting of the steel, impurity control, property tests, techniques for hot isostatic pressing (HIP) joining and coating, experiments on interaction with plasma, activation analysis and work on a database for nuclear materials.

2. Development of CLAM

Design of the chemical composition of CLAM is based on a wide investigation of several on-going

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Table 1
Specification of the chemical compositions of some RAFMs (wt%)

Item	CLAM	F82H	JLF-1	EUROFER97	ORNL 9Cr–2WVTa
Fe	Bal.	Bal.	Bal.	Bal.	Bal.
Cr	9.0 ± 0.1	8.0	9.0	8.0–9.0	8.5–9.0
C	0.10 ± 0.02	0.1	0.1	0.10–0.12	0.1
Mn	0.45 ± 0.05	0.5	0.45	0.4–0.6	0.45
P	<0.003	<0.02		<0.005	
S	<0.002	<0.01		<0.005	
B		0.003		0.004–0.006	
N	<0.02	<0.01	0.05	0.02–0.04	
W	1.5 ± 0.1	2.0	2.0	1.0–1.2	2.0
Ta	0.15 ± 0.03	0.04	0.07	0.06–0.10	0.07
Si	<0.01	0.1	<0.1	<0.05	0.2
Ti	<0.006			<0.01	
V	0.20 ± 0.02	0.2	0.19	0.2–0.3	0.25

international research and development programs on RAFMs [8–10], but with unique characteristics as shown in Table 1. Impurities such as Co, Nb, Ag, Mo, Ni, etc. should be controlled as low as possible or eliminated. The content of Cr is designed as 9% in order to get the minimum ductile-brittle transition temperature (DBTT) both before and after irradiation [8]. The content of W is chosen as 1.5% in order to decrease the possibility of Laves phase precipitation and maintain enough strength. A small percentage of Ta is added to refine the grain size and to improve creep resistance at elevated temperature [10]. The addition of Mn is to replace nickel and to improve the mechanical properties and compatibility with LiPb.

Several small heats of 4.5 kg and 20 kg were prepared from 2002 to 2005 and a heat of 300 kg was fabricated in 2006. Larger ingots of 500 kg to one ton are planned. The normalization is performed at 980 °C for 30 min and then tempering is done at 760 °C for 90 min. Microstructure of CLAM after the heat treatment was observed by optical microscopy and transmission electron microscopy (TEM). The optical microscopy observation (see Fig. 1) shows that there was no δ ferrite in CLAM, the TEM image (see Fig. 2) shows that the microstructures of CLAM are mixture of lath-martensite phase and well-tempered martensite phase, and the lath structure is very fine [11].

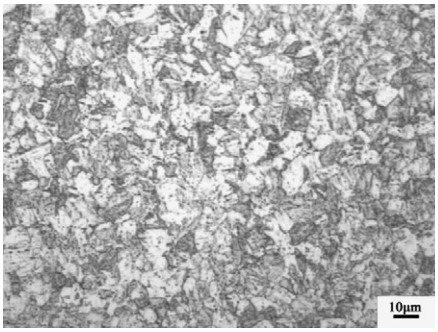


Fig. 1. Metallurgical structure of CLAM by optical microscopy.

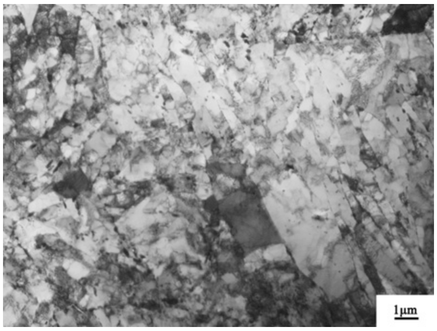


Fig. 2. Microstructure of CLAM by TEM.

Some physical and mechanical properties have been tested and are listed in Tables 2 and 3 [12]. The density is 7.78 g/cm^3. The thermal conductivity at room temperature is 24.5 W/(m K), and the thermal conductivity and thermal expansion coefficient at 600 °C are 28.3 W/(m K) and 12.5×10^{-6}/K, respectively. The ultimate and yield strengths for bar of CLAM are 668 MPa and 514 MPa at room temperature, 334 MPa and 293 MPa at 600 °C, respectively. The tensile properties are comparable with those of EUROFER97 [13]. The DBTT for standard specimens is about −100 °C [11]. Some experiments on plasma interactions with CLAM in HT-7 have also been done, and the results were published. [14,15].

The compositions and heat treatments will be optimized further. Other mechanical properties, such as creep, fatigue and properties after irradiation are going to be tested.

3. Coating and related issues

Experiments on the compatibility of the CLAM with liquid LiPb are being carried out in order to analyze and evaluate the corrosion behavior and mechanical degradation of CLAM in flowing liquid LiPb.

Coating is proposed as the primary solution to some key issues existing in a self-cooled liquid LiPb

Table 2
Physical properties of CLAM (HEAT 0408B)

Temperature (°C)	Specific heat (J/(kg K))	Thermal conductivity (W/(m K))	Linear expansion coefficient (10^{-6}/K)	Yang's modulus (GPa)	Poisson ratio	Electrical resistivity ($10^{-7}\Omega$ m)
25	431	24.5	–	218	0.30	4.72
100	483	26.5	11.1	213	0.30	5.28
200	521	27.0	11.5	208	0.29	6.18
300	573	27.9	11.8	202	0.29	7.15
400	626	28.1	12.0	194	0.30	8.09
500	693	28.4	12.3	183	0.29	8.99
600	795	28.3	12.5	168	0.29	9.82

Table 3
Tensile properties of CLAM

Tensile properties	HEAT 0211A		HEAT 0408A		HEAT 0408B	
	25 °C	350 °C	25 °C	600 °C	25 °C	600 °C
Ultimate strength (MPa)	651	488	668	334	670	373
Yield strength (MPa)	469	399	514	293	512	327
Total elongation (%)	27	18	25	29	25	19
Reduction of area (%)	–	–	77	87	–	–

blanket design. It needs to meet the following requirements: (i) tritium barriers to reduce tritium permeation, (ii) electrical insulator to mitigate Magnetohydrodynamic (MHD) effects in liquid metal tritium breeding blanket, (iii) corrosion barriers to permit higher temperature operation. Al_2O_3 is chosen as the candidate coating material in FDS designs. Some experiments were done with chemical vapor deposition (CVD). The coating layer produced at 700 °C has uniform thickness, dense structure, high aluminum composition, high micro-hardness, high electrical resistivity and pure Al_2O_3 on the surface of the layer [16]. The consistent examination of the coating with liquid LiPb will soon be carried out in statistic LiPb capsule and flowing LiPb loop, respectively. In addition, research on other methods for developing Al_2O_3 coatings are underway in order to obtain higher quality coating on CLAM to be applicable in the future test blanket module and reactor, e.g. in ITER TBMs [17,18].

4. Joining techniques and fabrication of blanket mock-up

HIP is a promising technology to fabricate the first wall (FW) and cooling plates of ITER TBM due to many advantages associated with a non-melting bonding technique. Many HIP experiments on RAFMs have been done [19,20]. The preliminary HIP experiments on CLAM have been done based on the work. The tensile properties of HIP joints are identical to base metal, while the impact property of the joints should be improved [21].

Optimization of HIP conditions is being carried out to get better joints and to maintain the properties of CLAM. In addition, great efforts are required to investigate the joining of the TBM components in the fabrication process, e.g. the joining of FW and cooling plates.

In the process of the component joining, the difficulties are how to make qualified joints without hurting the nearby channels and how to control and decrease the residual deformation caused by the welding. Currently researches on electron beam welding (EBW), laser beam welding (LBW) and tungsten insert gas welding (TIG) for RAFMs are being carried out to explore suitable techniques for joining the blanket components.

R&D activities on fabrication of a blanket mock-up with CLAM are currently being planned in order to successfully fabricate an ITER TBM in the future. A mini-mockup of one-fifth scale will be fabricated to confirm the feasibility of the joining technique, and a one-third scale mockup will be manufactured and tested in Experimental Advanced Superconducting Tokamak in China (EAST) device [22] in China before being tested in ITER. EAST can serve as a pre-testing platform for ITER TBM because the basic electromagnetic parameters and the average heat flux density at the FW in EAST are comparable to those in ITER. The data and experiences from EAST-TBM operation could be very helpful to optimize and improve the TBM designs [17,18].

5. Activation simulation and analysis

A lot of work on activation simulations and analysis of CLAM has been done based on the FDS series blanket designs [23–27]. The main conclusions are as follows:

(1) There is almost no difference in total activation values among the RAFMs for shorter cooling time, but the differences among them become larger with longer cooling time due to dominant nuclides with different half-lives. The dominant nuclides at shorter cooling time are mainly from activation of the major elements in the steels, which are very similar for all RAFMs. However, the dominant nuclides at longer cooling time are mainly from activation of impurities in the steels, which are quite different for each steel.

(2) When using CLAM as the FW material in FDS designs, dose rates reduce to the remote handling level [28] after 100 years, and it will not be reduced to the hands-on recycling level [28] even for a cooling time of as long as 10^4 years.

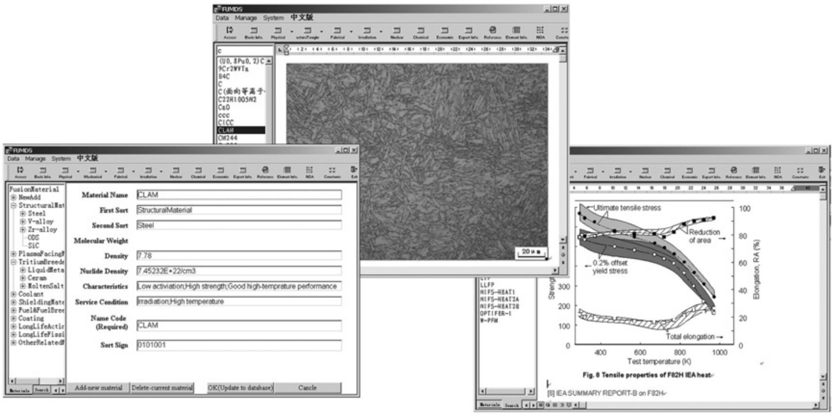
(3) To meet the requirement for remote handling, the required control levels for impurities in CLAM, such as Nb, Ag, Ni and Ho, are very high, while that for Mo or Co are relatively lower.

(4) Short-lived nuclides ^{60}Co and ^{55}Fe dominate the total dose rate of CLAM for a cooling time less than 100 years. After that, the long-lived nuclide ^{94}Nb becomes the dominant nuclide.

6. Fusion materials database system

As stated above, several tests and R&D activities on structural material CLAM and related technologies were completed or are underway in ASIPP. A lot of data, test results and related information arose, and the database will be updated from time to time. It is necessary to collect the data to establish a systematic and hierarchical database for analysis of various properties and for further optimization and redesign of CLAM. Development of the Fusion Materials Database System (FUMDS) is underway in ASIPP based on other databases established and under development in other countries [29–32]. For analysis and comparison with data on other fusion structural materials, the database is extended to include data on worldwide researched RAFMs, V-alloys and SiC$_f$/SiC composites etc. For synthetic considering and analysis, achievements and test results of nuclear materials for fission applications are also collected in FUMDS.

Its characteristics includes: (1) almost all nuclear materials contained; (2) detailed and hierarchical information collected; (3) various data type included; (4) practical and convenient software based on network. Fig. 3 shows some examples of the FUMDS interfaces. In addition, to make it more practical and convenient, the chemical periodic table, nuclide density calculation sub-module and some common physical constants etc. are also included in FUMDS.



Material Name: CLAM
First Sort: StructuralMaterial
Second Sort: Steel
Molecular Weight:
Density: 7.78
Nuclide Density: 7.45232E+22/cm3
Characteristics: Low activiation,High strength,Good high-temprature performance
Service Condition: Irradiation,High temperature
Name Code (Required): CLAM
Sort Sign: 0101001

Fig. 8 Tensile properties of F82H IEA heat

[8] IEA SUMMARY REPORT-B on F82H

Fig. 3. Interface for browsing and searching of materials data in FUMDS.

7. Summary

A series of R&D activities on the structural material CLAM and related technology are being carried out in ASIPP under wide collaboration with other institutes and universities in China and overseas. This includes smelting, controlling of the chemical composition, property tests, techniques for joining and coating, corrosion properties with liquid LiPb and irradiation effects from plasma. It is clear that CLAM shows some good properties before irradiation from current tests.

Substantial simulation and analyses on activation characteristics of CLAM and on contributions of impurities to total dose rate have been done. A nuclear materials database FUMDS has been developed.

Optimization of composition, property tests after irradiation and related work for large ingots are underway.

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