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PROGRESS ON THE ENGINEERING QUALIFICATION OF CN-RAFM STEEL

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Abstract

CN-RAFM steels (CLF-1 and CLAM), as structural materials candidate for the China ITER-HCCB-TBM (International Thermonuclear Experimental Reactor-Helium Cooled Ceramic Breeder-Test Blanket Module) module, have undergone engineering qualification since 2021, which includes 1) the production and fabrication of base materials, welds, and 2) large-scale tests of materials, to obtain Particular Material Appraisals (PMA) and provide support for material selection. In this paper, the recent progress on the engineering qualification of CN-RAFM steels is presented. Three 5-ton-scale CN-RAFM steels ingots for each have been manufactured using Vacuum Induction Melting + Vacuum Consumable Remelting (VIM + VAR) smelting process, and the corresponding 10 mm, 30 mm, 50 mm rolled plates and 130 mm forged plates were produced. To obtain applicable welding methods for manufacturing TBM modules, welding procedure qualification was completed for 10 mm Laser Beam Welds (LBW), 30 mm Tungsten Inert Gas welds (TIG), and 50 mm Electron Beam Welds (EBW), respectively. It indicates that the manufacturing of different thicknesses plates and the welds show strong stability and are viable for large-scale engineering applications. For the engineering qualification tests, short-term properties tests of CLF-1 base steels, different CLF-1 welds, and CLAM base steels have been completed, and long-term tests such as creep and fatigue are underway. All testing results obtained so far meet the requirements of the task target. The main differences between the two CN-RAFM steels are the chemical composition of the material, preparation process, welding parameters, and properties test results. Engineering qualification is expected to be completed by 2026.

1. INTRODUCTION

The Tritium Breeding Blanket (TBB) of fusion reactors serves as a critical component of the reactor core, responsible for key functions such as tritium self-sustaining, energy extraction, and radiation shielding. According to China's fusion development strategy, the HCCB TBS has been selected as the experimental system through which China participates in the ITER-TBM program, to verify the key technologies of TBB [1]. Reduced Activation Ferritic/Martensitic (RAFM) steel has been selected as the structural material for ITER-TBM due to its excellent thermo-physical and thermo-mechanical properties, excellent resistance to neutron irradiation embrittlement and radiation swelling, short-term radioactive nuclide production after neutron irradiation, mature industrial manufacturing technology foundation, and relatively low manufacturing cost. It is also the preferred structural material for TBB in future fusion reactors [2-5].

Based on the following objectives: 1) to ensure the large-scale manufacturing capability of structural materials for ITER-TBM and future fusion reactor blanket, 2) to provide a comprehensive database for the optimized design of HCCB-TBM and future fusion reactor blanket, 3) to support the selection of structural materials for HCCB-TBM, and 4) to obtain PMA for pressure equipment as required by EU and French regulations, supported by the CN DA (China Domestic Agency) of the Ministry of Science and Technology, the Southwestern Institute of Physics (SWIP) has launched engineering qualification work for two types of CN-RAFM steels (CLF-1 and CLAM) since 2021. The flowchart of engineering qualification is shown in Fig. 1.

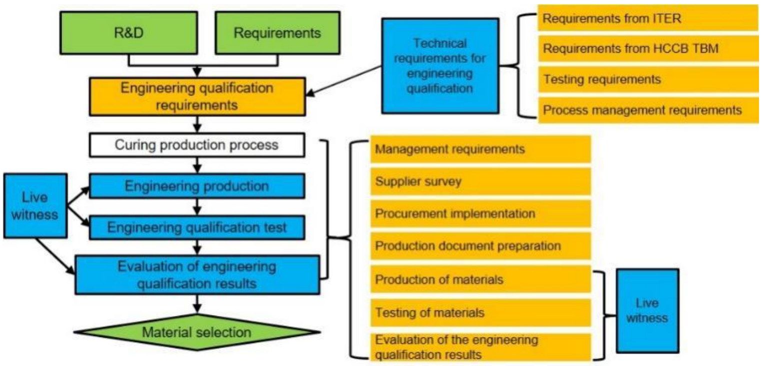

FIG. 1. The flowchart of the CN-RAFM steel engineering qualification.

According to the implementation plan of CN-RAFM steel engineering qualification, the qualification work mainly includes two parts. The first part is the production and fabrication of engineering qualification base materials and welds, and the second part is the engineering qualification tests of base materials and welds. The relevant testing items are summarized in Table 1, including on-site testing, factory testing, chemical composition, microstructure, physical properties, and mechanical properties tests.

TABLE 1. ENGINEERING QUALIFICATION TESTING CONTENS

Testing contents	On-site testing during production process	Final factory testing	Testing for base steel	Testing for welds
Dimension and shape	○	●	NA	○
Marking	○	●	NA	●
Chemical composition	●	●	●	●
Microstructure	○	●	●	●
Grain Size	○	●	●	●
Inclusions	○	●	●	○
Visual test	○	●	○	●
Penetration test	○	●	○	●
Ultrasonic test	○	●	○	●
Physical property	NA	NA	●	○
Tensile property	○	●	●	●
Impact property	○	●	●	●
Fatigue property	NA	NA	●	●
Creep property	NA	NA	●	●
Compatibility with coolant	NA	NA	●	○
Thermal aging	NA	NA	●	●
Vacuum property	NA	NA	●	○
Note	●: Must be tested ○: Optional NA: Not applicable			

2. CLF-1 STEEL ENGINEERING QUALIFICATION

2.1. Production manufacturing of CLF-1 base steel and welds

In accordance with Reference Procurement Specification (RPS) of engineering qualification product manufacturing, three 5-ton-scale CLF-1 steel ingots were manufactured using VIM + VAR process. From these ingots, 10 mm, 30 mm, 50 mm rolled plates and 130 mm forged plates were produced through forging, hot rolling, heat treatment, machining, non-destructive testing processes, etc. The 5-ton-scale CLF-1 steel ingots and products with different thicknesses are shown in Fig. 2, and their chemical compositions are listed in Table 2. Using CLF-1 steel rolled plate products, welding procedure qualifications were performed for 10 mm Laser Beam Welds (LBW), 30 mm Tungsten Inert Gas welds (TIG), and 50 mm Electron Beam Welds (EBW), respectively. By using the same welding process, more than 20 test plates for comprehensive properties evaluation were welded for each welding method separately. The welding methods, processes, and properties testing plates are shown in Fig. 3. The results of CLF-1 base steel and weld production demonstrate that the manufacturing processes for plates of different thicknesses and their corresponding welds exhibit strong stability and are suitable for large-scale engineering application.

FIG. 2. The 5-ton-scale CLF-1 steel ingots and corresponding products with different thicknesses.

TABLE 2. THE CHEMICAL COMPOSITION OF CLF-1 STEEL INGOTS AND PRODUCTS

Element	Required value (wt.%)	Measured value (wt.%)						
		Ingot-1	Ingot-2	Ingot-3	10 mm Rolled plate	30 mm Rolled plate	50 mm Rolled plate	130 mm Forged plate
C	0.080~0.135	0.124	0.110	0.116	0.120	0.123	0.122	0.121
Cr	8.2~8.8	8.78	8.76	8.64	8.68	8.66	8.69	8.69
W	1.3~1.7	1.55	1.49	1.50	1.52	1.47	1.48	1.49
Mn	0.3~0.7	0.55	0.52	0.50	0.58	0.55	0.54	0.57
Ta	0.05~0.15	0.10	0.096	0.10	0.10	0.11	0.11	0.11
V	0.2~0.4	0.32	0.31	0.32	0.33	0.33	0.33	0.32
N	0.015~0.040	0.016	0.015	0.016	0.017	0.016	0.017	0.016
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

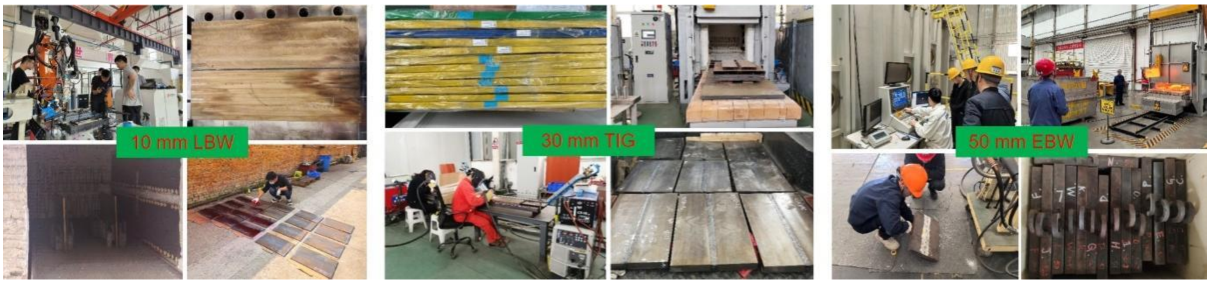

FIG. 3. The different welding methods, process, and properties testing plates of CLF-1 steel.

2.2. Engineering qualification tests of CLF-1 steel

Following the engineering qualification testing plan, the chemical composition, microstructure (structure, grain size, inclusions), physical properties (thermal, magnetic and electrical, measured from RT ~ 700 ℃), vacuum properties, tensile properties (RT ~ 700 ℃), impact properties (-120 ℃~ RT), fracture toughness (RT ~ 600 ℃), high-temperature long-term aging (550 ℃ for more than 3000 h), and compatibility with coolant (550 ℃ at 8 MPa He for more than 3000 h) of CLF-1 base steel have been evaluated. Creep and fatigue properties are currently being tested. For different types of welds of CLF-1 steel, microstructure, tensile properties (RT ~ 700 ℃), impact properties (-120 ℃~ RT), fracture toughness (RT ~ 600 ℃) and other tests have been completed, while creep and fatigue properties tests are also currently underway. All results obtained so far meet the requirements of the task target, and the partial engineering qualification testing devices and results are shown in Fig. 4.

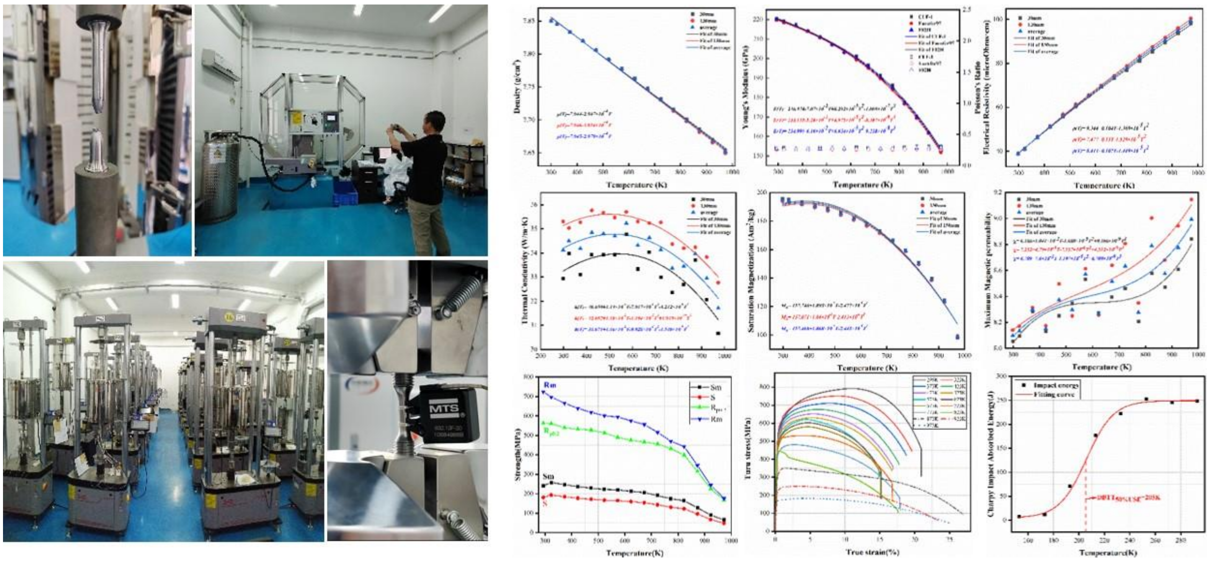

FIG. 4. The partial engineering qualification testing devices and results of CLF-1 steel.

3. CLAM STEEL ENGINEERING QUALIFICATION

The engineering qualification process for CLAM steel is similar to that of CLF-1 steel, which includes the manufacturing of base metal and weld products, as well as engineering qualification test. The main differences between the two lie in their chemical composition, preparation process, welding parameters, and properties test results.

3.1. Production manufacturing of CLAM base steel and welds

Similarly, CLAM steel was prepared using VIM + VAR process to produce three 5-ton-scale ingots, which were subsequently forged, hot-rolled, heat-treated, machined, and non-destructively tested to produce 10 mm, 30 mm, 50 mm rolled plates and 130 mm forged plates. The three ingots and their products of different thicknesses are shown in Fig. 5, and their chemical compositions are listed in Table 3. Using CLAM steel rolled plate products, qualification of welding procedure was completed for 10 mm LBW and 50 mm LBW using laser and electron beam welding methods, respectively. As with CLF-1, more than 20 test plates for comprehensive property evaluation were welded for each method using the same process. The welding method, process, and properties testing plates are presented in Fig. 6. The results show that the preparation process stability of CLAM steel across different thicknesses of base materials is comparable to that of CLF-1 steel, demonstrating its suitability for large-scale engineering applications. Optimization and qualification of 30 mm TIG welding process are currently underway.

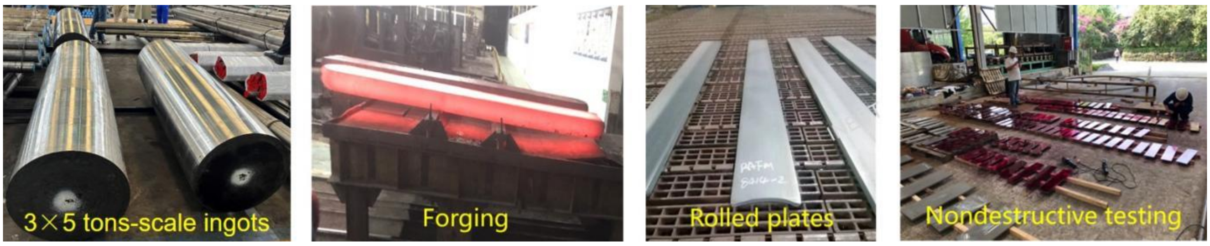

FIG. 5. The 5-ton-scale CLAM steel ingots and corresponding products with different thicknesses.

TABLE 3. THE CHEMICAL COMPOSITION OF CLAM STEEL INGOTS AND PRODUCTS

Element	Required value (wt.%)	Measured value (wt.%)						
		Ingot-1	Ingot-2	Ingot-3	10mm Rolled plate	30mm Rolled plate	50mm Rolled plate	130mm Forged plate

C	0.080~0.135	0.092	0.095	0.087	0.11	0.10	0.10	0.10
Cr	8.2~9.5	8.93	9.02	8.95	9.02	9.03	8.98	8.98
W	1.0~2.0	1.56	1.56	1.57	1.51	1.52	1.55	1.54
Mn	0.2~0.7	0.40	0.40	0.23	0.47	0.51	0.56	0.49
Ta	0.05~0.15	0.12	0.12	0.12	0.13	0.13	0.13	0.13
V	0.15~0.40	0.20	0.20	0.20	0.20	0.19	0.20	0.20
N	≤0.02	＜0.002	0.0022	0.0025	0.0025	0.0025	0.0027	＜0.002
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

FIG. 6. The different welding methods, process, and properties testing plates of CLAM steel.

3.2. Engineering qualification tests of CLAM steel

For engineering qualification tests, short-term property evaluations of CLAM steel base steel have been completed, while long-term tests such as creep and fatigue are still ongoing. For CLAM steel welds, tensile and impact tests of the 50 mm EBW welds have been carried out. The partial engineering certification test results are shown in Fig. 7.

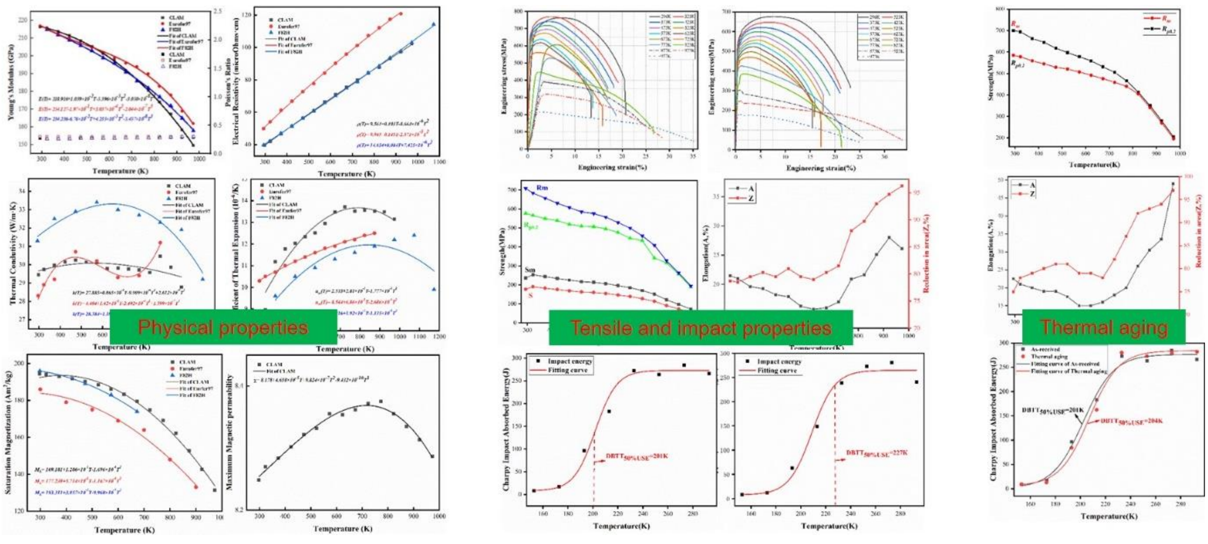

FIG. 7. The partial engineering qualification testing results of CLAM steel.

4. SUMMARY AND NEXT PLAN

Engineering qualification for the candidate structural materials for CN-HCCB-TBM was launched in 2021, with the objectives of ensuring large-scale production capability for TBM manufacture, establishing a comprehensive database, providing a basis for material selection, and obtaining PMA for pressure equipment. Three 5-tons ingots and 10 mm, 30 mm, 50 mm rolled plates as well as 130 mm forgings of CN-RAFMs steels, along with the corresponding 10 mm LBW, 30 mm TIG, 50 mm EBW welds were manufactured. The engineering qualification tests are ongoing and are expected to be completed by 2026. Upon completion of the engineering qualifications, the CN-RAFM steels will be selected, followed by neutron irradiation and Post Irradiation Examination (PIE).

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