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Thermal-stress analysis of IFMIF target back-wall made of reduced-activation ferritic steel and austenitic stainless steel

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ABSTRACT

For long time operation of a liquid lithium target of the International Fusion Materials Irradiation Facility, annual replacement of a back-wall, a part of the flow channel, is planned, since the target suffers neutron damage of more than 50 dpa/fpy. Considering irradiation/activation conditions, remote weld on stainless steel 316L between a back-wall and a target assembly was employed. Furthermore, dissimilar weld between the 316L and a reduced-activation ferritic/martensitic steel F82H in the back-wall was employed. The objective of this study is to clarify structures and materials of the back-wall with acceptable thermal-stress under nuclear heating. Thermal-stress analysis was done using a code ABAQUS and data of the nuclear heating. As a result, thermal-stress in the back-wall is acceptable level, if thickness of the stress-mitigation part is more than 5 mm. With results of the analysis, necessity of material data for F82H and 316L under conditions of irradiation tests and mechanical tests are clarified.

1. Introduction

To develop neutron irradiation facilities for testing effects of neutron irradiation upon properties of candidate materials for fusion reactors, activities for the International Fusion Materials Irradiation Facility (IFMIF) were started in 1995, and further succeeded by the IFMIF Engineering Validation and Engineering Design Activity (IFMIF-EVEDA) [1].

Fig. 1 shows the IFMIF target section. To provide an intense neutron flux with a peak energy around 14 MeV well simulating a fusion neutron, two deuteron (D^+) beams with a total current of 250 mA and an energy of 40 MeV are injected into a flowing liquid lithium (Li) target operated at flow speed of 10–20 m/s for removal of 10 MW heat deposited by the D^+ beams and for suppression of excessive increase of Li temperature which can bring excessive Li vaporization at the free surface or Li boiling inside the flow. In a test volume, estimated damage rate on Fe-base specimen is more than 50 dpa/fpy (displacement per atom/full power year) at 0.1 l, 20 dpa/fpy at 0.5 l and 1 dpa/fpy at 6 l. Also every component around the target is damaged by the neutron flux. Especially, the back-wall part of the target assembly is suffered annual damage about 50 dpa, and thus, the back-wall is replaced in annual maintenance after every 11 months operation.

Due to mentioned severe damage and high activation, the back-wall is designed to have two types of weld parts. One is a lip part at its circumference made of stainless steel 316L. Several times of remote cut and re-weld between both lip parts of the back-wall and the target assembly, both made of 316L, are done by using a YAG laser tool. The other is dissimilar weld between the lip part and a center part made of reduced-activation ferritic/martensitic (RAFM) steel such as F82H. The dissimilar weld is done only once in fabrication, and thus manual works close to back-walls are available.

This paper presents thermal-stress analysis for design of the back-wall including the lip-weld part and the dissimilar-weld part with acceptable thermal-stress even under the heating condition during beam injection. With analysis results, conditions of irradiation tests and mechanical tests to be done in IFMIF-EVEDA are proposed.

2. Thermal-stress analysis of back-wall

Thermal-stress analysis of the back-wall and its connecting part of the target assembly under nuclear heating considering normal operation of IFMIF target with 10 MW D^+ beams was done by using a calculation code ABAQUS [2].

2.1. Analysis condition

An input model of the back-wall ($Z > 0$ mm) and the connecting part of target assembly ($Z < 0$ mm) is shown in Fig. 2. Because of symmetry to X–Z plane and Y–Z plane, 1/4 part of the back-wall was employed as the model. The Z axis corresponds to the center line of D^+-beam. A shape of the back-wall almost likes a disk, but

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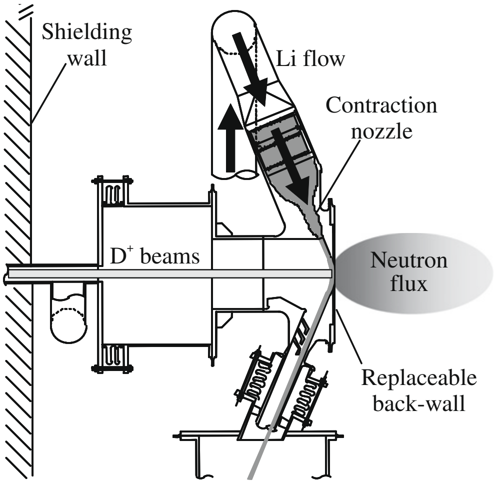

Fig. 1. IFMIF target section.

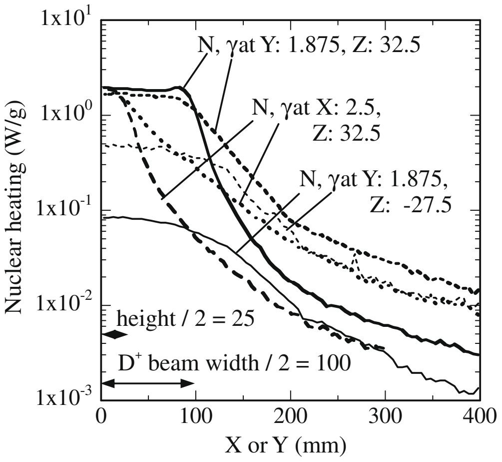

Fig. 3. Nuclear heat (Simakov, unit of length: mm).

the back-wall has a concave flow channel for liquid Li with radius 250 mm and width 260 mm at the center. The minimum thickness of the back-wall is 1.8 mm at the location $-130 < X$ (mm) < 130, $Y = 0$ mm to utilize the neutron flux efficiently. Previous analysis showed effectiveness of a stress-mitigation part adapted to both of the circumference of the back-wall and its connecting part of the target assembly [3]. In this analysis, thickness of the stress mitigation: t_{SM} of 2, 5 or 8 mm was employed.

Input data of nuclear heating ware based on those due to neutron through Li(D, xn) and secondary gamma through Li(n, $x\gamma$), which are shown in Fig. 3, calculated by Simakov with McDeLicious code [4]. The maximum heating is 3.6 W/g (neutron: 1.9, γ: 1. 7) or 28 W/cm^3 for F82H at the beam center. The heating on the thinnest part is almost uniform within the range of D$^+$-beam width $-100 < X$ (mm) < 100.

Materials of the back-wall are the RAFM steel F82H (Cr: 8%, W: 2%, V: 0.14%, Ta: 0.04%, C: 0.1% in weight) for its center part: $R < 330$ mm and the stainless steel 316L (Cr: 16–18%, Ni: 12–15%, Mo: 2–3%, Mn < 2%, Si < 1%, C < 0.03%) for the other part: $R > 330$ mm as shown in Fig. 2. The target assembly is made of 316L only. Material properties of F82H and 316L are shown in Fig. 4. A filler metal for the dissimilar weld was neglected in the analysis.

Boundary conditions were as follows: heat transfer between the back-wall and liquid Li at 300 °C was 34 kW/m^2 K [5]. The temperature of 300 °C was adapted to also the outer boundary of the target assembly: $Z = -30$ mm, since temperature of most part of the target assembly with weight of about 1 ton can be assumed uniform at 300 °C due to the Li flow and thermal insulation. At the other outer surface, radiation to an environment with a temperature of 50 °C with an emissivity of 0.3 was adapted, considering the minimum temperature of IFMIF vertical test assembly installed 2 mm apart from the back-wall (i.e. $Z = 37$ mm). For the gap between the back-wall and the target assembly (i.e. $Z = 0$ mm, $R < 380$ mm), a heat transfer coefficient of 20.5 W/m^2 K was adopted assuming a contact pressure of 0.1 MPa due to only cover gas (He or Ar) in Test Cell room.

2.2. Analysis results and discussion

Thermal analysis and thermal-stress analysis were done for the IFMIF back-wall model with changing the thickness of stress-mit-

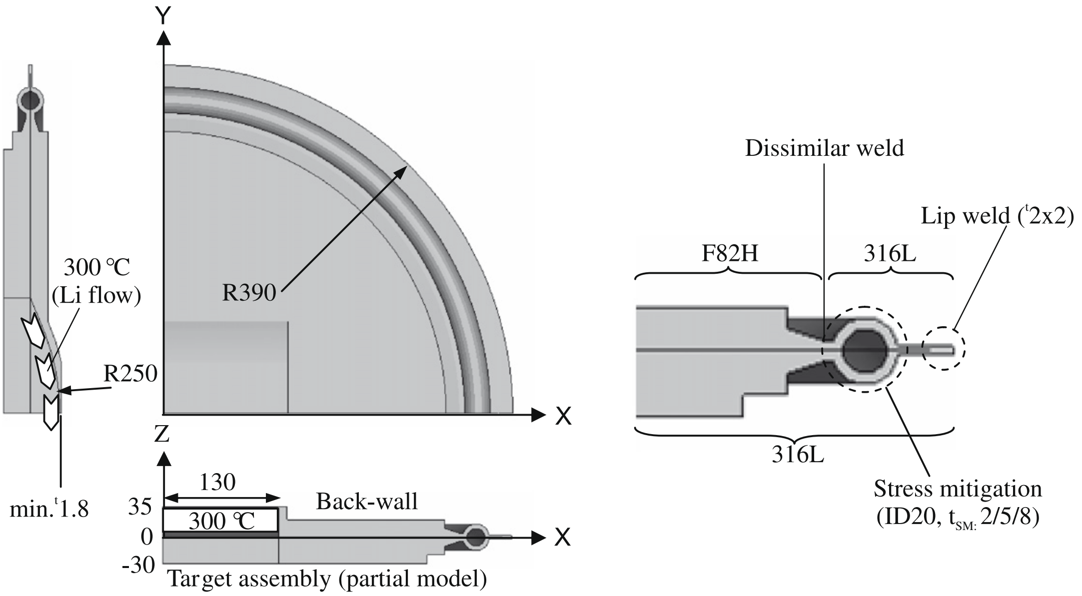

Fig. 2. Back-wall model (unit of length: mm).

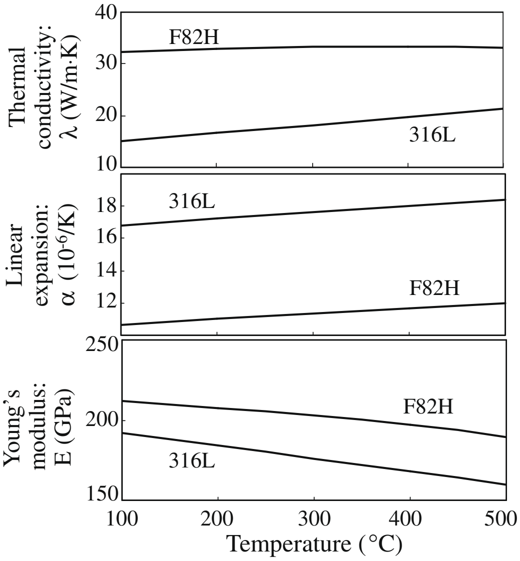

Fig. 4. Material properties of F82H and 316L.

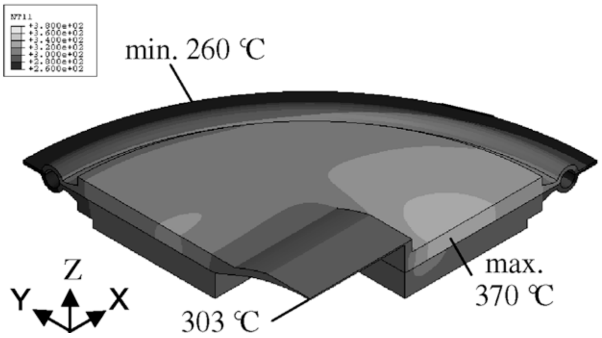

Fig. 5. Temperature in back-wall (t_{SM} = 5 mm).

igation part: t_{SM} = 2, 5 or 8 mm. For an example, a typical result of calculated temperature in a case: t_{SM} = 5 mm is shown in Fig. 5. Temperature of the center was 303 °C even with the maximum heating of 28 W/cm^3, since the thin concave part made of F82H was well cooled by the Li flow with the temperature 300 °C. The maximum temperature 370 °C was given near a location *X*: 20 mm, *Y*: 0 mm, *Z*: 10 mm in the 20 mm-thick part made of F82H, while nuclear heating at the location was only 0.5 W/cm^3. Also in the other cases t_{SM} = 2 or 8 mm, the maximum temperature 369–370 °C was given at the location. In this analysis, the contact pressure between the back-wall (made of F82H) and the target assembly (316L) was conservatively assumed 0.1 MPa considering only cover gas pressure in the Test Cell. This pressure value corresponds to a heat transfer coefficient of 20.5 W/m^2 K. An actual back-wall is preliminarily designed to be pressed to the target assembly by a mechanical clamp with increasing the contact pressure up to 0.5 MPa, which corresponds to a heat transfer coefficient of about 100 W/m^2 K. This condition reduces the maximum temperature. Therefore, it is sufficient for us to consider property of F82H in a temperature range up to 370 °C in normal operations. The minimum temperature 232, 260 and 267 °C was given at circumference in cases of t_{SM} = 2, 5 and 8 mm, respectively. In any cases, temperature in the lip-weld part ($R > 380$ mm) made of 316L did not exceed 287 °C, and temperature in the dissimilar weld (F82H-316L) part ($R = 330$ mm) did not exceed 332 °C. The maximum temperature of the target assembly was 327 °C in this analysis with assuming the minimum contact pressure of 0.1 MPa. The temperature possibly increases close to 370 °C under a condition of well contact.

Table 1
Results of thermal-stress analysis.

Cases	von Mises stress (MPa)			Displacement (mm)		
	Back-wall (A[a])	Back-wall (B[a])	Stress-mitigation part	ΔX	ΔY	ΔZ
t_{SM}: 2 mm	140	170	500	0.17	0.15	−0.80
t_{SM}: 5 mm	149	144	326	0.15	0.13	−0.32
t_{SM}: 8 mm	155	140	280	0.14	0.13	−0.19
Allowable value	455 (F82H, 300 °C)	455 (F82H, 300 °C)	328 (316L, 300 °C)			

[a] A: thin concave part of back-wall, B: side-wall of flow channel.

Results of thermal-stress analysis are summarized in Table 1. For design of the IFMIF back-wall and target assembly, allowable stress is defined to be $3S_m$ [3] according to ASME code, where S_m is the minimum value among $(2/3)S_y$ and $(1/3)S_u$. In the previous and this analyses, S_y and S_u were, respectively, yield strength and ultimate tensile strength of F82H [6] and 316L [7] without neutron irradiation. Fig. 6 shows calculated stress (von Mises stress) in a case t_{SM} = 5 mm, which was the minimum thickness to control the thermal-stress below acceptable level. In this case, the maximum stress in F82H part ($Z > 0$ mm, $R < 330$ mm) and in 316L part was respectively 149 MPa at the thin concave part and 326 MPa at the stress-mitigation part. In any cases, the maximum stress in F82H was given at the concave part (A in Table 1) or side-wall of flow channel ($X = 130$ mm, B in Table 1), and the stress was far lower than the acceptable level for F82H. Integrities of the both parts directly impact on stability of the Li flow. Therefore, employment of F82H as material of the back-wall center part is reasonable from the viewpoints of stress and activation. On the other hand, the maximum stress in 316L, which was given around the stress-mitigation part in any cases, was 500, 326 and 280 MPa in cases of t_{SM} = 2, 5 and 8 mm, respectively. These are close to the acceptable value for 316L or higher. Stress-mitigation part with thickness of 5 mm or more is needed to assure integrity of the back-wall in operation. (See Table 2).

Calculated displacement in the case t_{SM} = 5 mm with acceptable stress is shown in Fig. 7 with a magnification factor of 100. Radial displacement up to 0.15 mm was well absorbed as deformation of the stress-mitigation part, and diameter of the back-wall increased by only 0.08 mm (0.04 × 2) at its circumference. The center thin part of the back-wall deformed by 0.32 mm in direction of $-Z$. The allowable displacement of the flow channel is to be defined through hydraulic estimations.

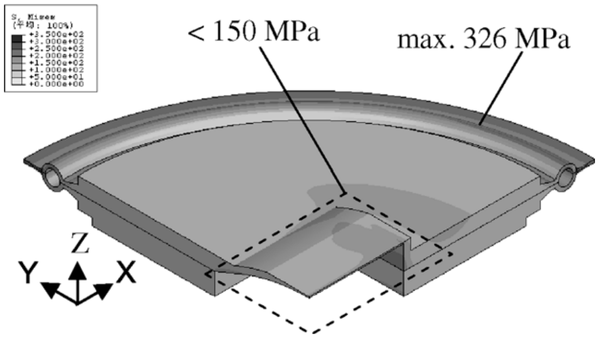

Fig. 6. von Mises stress in back-wall (t_{SM} = 5 mm).

Table 2
Irradiation condition in operation.

Part	Material	Temperature (°C)	Neutron heating (W/g)	Gamma heating (W/g)	Operation duration
Back-wall (center)	F82H	<400	1.9	1.7	11 months
Dissimilar weld	F82H-316L	<350	2.1×10^{-3}	1.4×10^{-2}	11 months
Lip weld	316L-316L	<300	1.6×10^{-3}	1.1×10^{-2}	11 months
Target assembly	316L	<400	6.5×10^{-2}	0.36	30 years

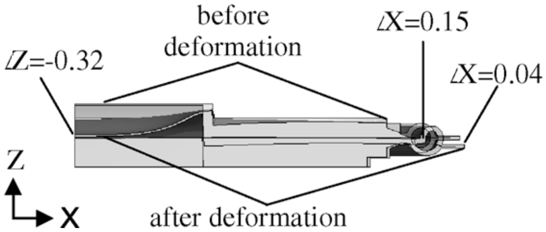

Fig. 7. Deformation of back-wall (t_{SM} = 5 mm).

3. Material issues toward IFMIF design

The thermal and thermal-stress analyses were done with existing data of RAFM steel F82H and stainless steel 316L. Toward engineering design of the IFMIF back-wall and target assembly in IFMIF-EVEDA to be completed until 2013, material data are to be obtained and estimated as follows.

3.1. Effects of irradiation upon material properties

While material data such as yield strength and ultimate tensile strength without irradiation were used in this analysis, irradiation data are necessary for engineering design of IFMIF. Each back-wall suffers the neutron/gamma irradiation in 11 month, and is replaced to new one through remote cut/re-weld at the lip part. On the other hand, the target assembly operates for 30 years with inspections after every 11 month operation. The maximum accumulated irradiation damage on F82H and 316L is roughly estimated 50 dpa, considering the neutron heating. Therefore, irradiation data up to 50 dpa on F82H and 316L under temperature condition up to 400 °C are to be obtained, while existing data for RAFMs [6,8] are available in regions of lower dose up to about 10 dpa. For the target assembly, annealing effects upon recovery of irradiation damage and annealing scheme in each 1 month maintenance are to be investigated. Also for the weld parts, irradiation data up to 1 dpa under temperature condition up to 350 °C are to be obtained.

3.2. Effects of welds upon material properties

Integrity of the lip weld and the dissimilar weld are to be assured toward the IFMIF engineering design. Mechanical tests, such as tensile test and hardness test, with weld specimen were stated under collaboration between Japan Atomic Energy Agency and Hachinohe National College of Technology [9]. In preliminary tensile tests on dissimilar weld (316L-F82H) specimen, the fracture was occurred in base metal of 316L. On the other hand, in case of lip weld (316L-316L), the fracture was occurred in the weld part. Considering the results of the thermal analysis, tensile tests on two types (316L-F82H, 316L-316L) of weld specimen under high temperature up to 400 °C are under going. For the dissimilar weld, effects of filler metal and heat treatment are investigated.

4. Conclusions

The thermal-stress analysis showed that the design of the back-wall was acceptable from view point of maximum von Mises stress in the back-wall center part made of F82H (allowable stress: 455 MPa at 300 °C) and in the other part made of 316L (328 MPa), if the thickness of stress-mitigation part: t_{SM} was 5 mm or more. In the case of t_{SM} = 5 mm, the maximum stress in each material was 149 MPa and 326 MPa, respectively, at the thin concave flow channel (F82H) and at the stress-mitigation part (316L). For the engineering design, necessity of material data for F82H and 316L under neutron irradiation conditions up to 50 dpa and up to 400 °C was clarified through the estimation of nuclear heating and the thermal-stress analysis.

Acknowledgement

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