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(別紙様式 2)
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論文内容の要旨

Summary of thesis contents

論文題目　Dissimilar-metal bondings for reduced-activation ferritic/martensitic steel, oxide-dispersion-strengthened steel, and stainless steel

It is essential to develop dissimilar-metal bondings for the construction of fusion blanket system. Two combinations of structural materials for dissimilar-metal bondings are investigated in the present study. One combination for bonding is advanced oxide-dispersion-strengthened reduced-activation ferritic/martensitic (ODS-RAFM) steel and conventional non-ODS RAFM steel. Because ODS-RAFM steel has excellent high-temperature strength and good irradiation resistance, the dissimilar-metal joint can be used in the first wall of blanket to locate the ODS-RAFM steel near the blanket surface and to enhance the acceptable heat load from the fusion plasma. In this concept, the acceptable temperature of the first wall will be improved to 700ºC from 550ºC of full-conventional-RAFM blanket concept. The other combination for bonding is conventional RAFM steel and stainless steel. This dissimilar-metal joint connects the blanket systems to the out-vessel components such as tritium extraction system and heat exchanger for power generation.

In the present study, the above mentioned dissimilar-metal joints were fabricated and evaluated for their mechanical properties and microstructures. The weld metal (WM), the heat-affected zones (HAZs), and the base metals (BMs), exhibited undesirable hardening or softening. However, the strength of the joints was successfully recovered by appropriate heat treatment after the bonding, i.e. post-weld heat treatment (PWHT). The mechanisms for the degradation and recovery were well understood by carbon behavior in the steels, such as phase transformation with carbide decomposition, carbon dissolution and re-precipitation, carbide coarsening and decarburization. In addition, mechanical property tests combined with finite element method (FEM) simulation, revealed better-estimated bonding strength of the joints compared with conventional analysis. One of the developed joints, a joint between conventional RAFM steel and stainless steel, was neutron-irradiated and showed good irradiation resistance.

1. Dissimilar-metal joints between 9Cr-ODS steel and JLF-1 steel

The dissimilar-metal joints between ODS-RAFM steel and non-ODS conventional steel will be used for the first wall structure and for the cooling channel connection near there. The former requires large area and three-dimensional-shape bonding with a typical cross section of 1 square meter, while the latter needs robust welding with high accuracy for several mm in thickness to resist the coolant pressure.

The ODS-RAFM steel used is designated as 9Cr-ODS, whereas the conventional RAFM steel is JLF-1. The chemical compositions are Fe-9.08Cr-1.97W-0.14C-0.23Ti-0.29Y and Fe-9.00Cr-1.98W-0.09C-0.20V-0.083Ta, respectively. Since the strengthening agent, nano-particle oxides, is decomposed in the WM during fusion (melt) welding, the single-metal joint for ODS steel is generally fabricated with non-fusion process, such as pressurized resistance welding in the research for fast breeder reactor, and hot iso-static pressing (HIP) and friction-stir welding (FSW) in the research for fusion reactor. However, the nano-particles are not necessarily required for the WM of the present dissimilar-metal joint, because the conventional RAFM steel does not contain nano-particles and accepts no oxide-dispersion strengthening if the WM is not softer than the BM of the conventional RAFM steel. Therefore, fusion welding, such as electron-beam welding (EBW), laser welding and arc-welding, is also the candidate process for the present dissimilar-metal joint.

Two bonding processes, HIP and EBW, are selected to fabricate fine dissimilar-metal joints in the present study, because the former is the most suitable for the large area with three-dimensional shape bonding, and the latter is suitable for robust welding with high accuracy. Only one earlier activity on the dissimilar-metal bonding is found in the world, and is EU activity. However, the effect of bonding condition on the mechanical properties and bonding mechanisms have not systematically investigated yet, therefore are the purposes of the present study.

1.1. HIP joints

Dissimilar-metal joints between 9Cr-ODS and JLF-1 were fabricated by HIP at 1000ºC, 1050ºC, and 1100ºC, under a pressure of 191 MPa for 3h with a cooling rate of 5ºC/min after the HIP. The HIP process induced undesirable hardening in the BM of JLF-1, and also undesirable softening at the bonding interface, irrespective of the HIP temperatures.

The hardening is due to the formation of quenched martensite, because the cooling rate after the HIP was enough for quenching before carbon diffusion in the BM of JLF-1. While, it was too slow for 9Cr-ODS, where coarse carbides observed on the grain boundaries evidently indicated much diffusion of the carbon before quenching. No quenching and the carbide coarsening resulted in the softening of the BM of 9Cr-ODS. For the recovery of both the hardening and softening in the BMs, PWHT with a rapid cooling at 36ºC/min was effective.

On the other hand, the softening at the interface is attributed to decarburization of the specimen surface during the HIP process before bonding, which produced no-particle soft layer there. The soft layer is clearly observed in 1000ºC-HIP specimen, and leads to very local deformation and almost no elongation of the joint in tensile tests. While, the elongation was improved very much at higher HIP temperatures, such as 1050ºC and 1100ºC. Disappearance of the no-particle layer was observed at these temperatures and was consistent with the improvement. It should be promoted by the decomposition of the $M_{23}C_6$ carbides at the high temperatures and the following diffusion of carbon into the no-particle layer. Actually, 1100ºC HIP resulted in lower strength of the BM of JLF-1 than 1050ºC HIP. This is likely because of coarsening of grain structures. Therefore, 1050ºC is the optimum HIP temperature for the present dissimilar-metal joint. The bonding strength was measured at the optimum 1050ºC-HIP condition. It is 1200 MPa at room temperature (RT) and 820 MPa at 550ºC.

1.2. EBW joint

Dissimilar-metal butt joint between 9Cr-ODS and JLF-1 was fabricated by EBW with an output of 15 mA and 150 V and with a speed of 2000 mm/min. The electron beam was at the butting position for the plates.

The hardness of WM and HAZs in both 9Cr-ODS and JLF-1 was much higher than the BMs. The WM and the HAZs are quenched martensite phase with occasional ferrite phase. The quenched martensite in the WM and HAZs contributes unacceptable hardening accompanied by ductility loss for the joint. Therefore, two conditions of PWHT were carried out to relieve the hardening and to recover the microstructures of WM and HAZs to the levels close to the BMs.

One condition of PWHT is only tempering at 720-780ºC for 1h. The tempering changes the quenched martensite into softer tempered martensite. As tempering temperature increased, the hardening of WM and HAZs was relieved. But, softening of both the BMs due to over-tempering was indicated in the hardness test. The complete recovery of the hardening of the WM is obtained by tempering at 780ºC for 1h. However, the softening in the BMs was remained to be recovered.

The other condition of PWHT is a combination of normalization at 1050ºC for 1h and then the complete-recovery tempering at 780ºC for 1h. Because of the normalization, residual ferrite disappeared. The whole microstructure including WM, HAZs and BMs is quenched martensite after the normalization. After the following tempering, the whole microstructure is tempered martensite. The hardness of the BMs was the same as the levels before welding. The PWHT is the optimum to relief the hardening of WM and HAZs without degradation of strength of the BMs.

All the specimens fractured at the BM of JLF-1 during tensile tests, because the interface is stronger than BM of JLF-1. In this situation, the bonding strength cannot be determined by tensile tests in the same way as the HIP joints, and is estimated larger than the ultimate tensile strength of JLF-1. In order to estimate the bonding strength of the joint more accurately, symmetric 4-point bend tests, which can concentrate the stress precisely at the WM, was executed for the joint. Bending stress can be calculated according to the theory of elasticity within only 0.25% in strain, though the joint shows large deformation with more than 10% in strain due to plastic deformation. Thus, FEM simulation was used to extend the analysis to large deformation condition in the bend tests.

The large deformation induces sliding at the contact area between the specimen and jig. The sliding must be also simulated for accurate analysis, which requires an input parameter of friction coefficient at the contact area. The friction coefficient was analyzed by fitting for the simulation to bend test experiments on BM-single-material specimens. According to the coincidence of the displacement-load curves between the simulation and the experiment, the friction coefficient was determined as 0.3 for the contact between 9Cr-ODS and jig at RT, 0.5 and 0.55 between JLF-1 and jig at RT and 550ºC, respectively. Because of the analysis on the friction, the simulation successfully calculated the stress distribution in the specimens up to strain of 20.0% at RT and 23.5% at 550ºC. The maximum stress applied to the weld metal of the joint is estimated as 854 MPa at RT and 505 MPa at 550ºC. The bonding strength is estimated to be larger than these stresses. The FEM simulation successfully made better estimation for bonding strength than tensile tests and conventional analysis on bend tests with the theory of elasticity.

2. Dissimilar-metal joint between F82H steel and 316L stainless steel made by EBW

The dissimilar-metal joint between conventional RAFM steel and stainless steel will be used for only the cooling channel connection behind the blanket near the vacuum vessel. Therefore, only EBW process was investigated in the present study.

The conventional RAFM steel used is F82H steel, whereas the stainless steel is 316L steel. The chemical compositions are Fe-7.71Cr-1.95W-0.16V-0.02Ta-0.16Mn-0.091C-0.001N and Fe-18.5Cr-11.4Ni-1.91Mo-0.0855V-1.23Mn-0.014C-0.0375N, respectively. The joint between F82H steel and 316L steel has been fabricated and evaluated for the base line properties previously. Therefore, their neutron irradiation properties were investigated for further evaluation of the joint under the operation condition in fusion reactor.

The butt joint between F82H steel and 316L steel plates with a thickness of 7 mm was made by EBW with an output of 20 mA and 150 V, and a welding speed of 2000 mm/min. The electron beam position was 0.2 mm shifted from the butting position toward 316L side according to previous studies. PWHT condition was also determined by the previous study as 680ºC for 1h.

Neutron irradiation was carried out for the joint at 300ºC with a neutron fluence of $5.6\pm0.1\times10^{23}$ n m^{-2}, which is equivalent to a dose of 0.1 dpa (displacement per atom). The joint will be located near the vacuum vessel and superconducting magnet in fusion reactors. The maximum dose for the vacuum vessel in ITER (International thermonuclear experimental reactor) has been estimated as 0.027 dpa. The neutron fluence at the magnets in commercial-grade reactor design is about 1×10^{23} n m^{-2}. Since the present irradiation dose was more than these conditions, it is enough to evaluate the resistance of the dissimilar-metal joint to neutron irradiation under fusion reactor condition.

Neutron irradiation induced hardening for the whole part of joint, such as BMs, WM, and HAZs. Hardness of the joint before irradiation ranged from 180 VHN (Vickers hardness number) to 250 VHN, while the one after the irradiation ranged from 230 VHN to 300 VHN. In addition, significant hardening area with 450 VHN in hardness and with a size of 50 micron was detected at the fine-grain HAZ of F82H. One of possible mechanisms for the significant hardening is irradiation-induced precipitations produced by the carbides decomposed during the welding. The PWHT condition with 680ºC for the irradiated specimens was determined by the previous study, mainly from the viewpoint to avoid softening of F82H steel by over-tempering. However, it was not enough to complete the recovery of the hardness change by the welding. The present study found a better PWHT condition as 750ºC for 1h from further investigation from the viewpoint of carbide precipitation control. This PWHT will suppress the significant irradiation hardening and should be examined under neutron irradiation in future.

Fortunately, the significant irradiation hardening observed in the HAZ of F82H did not degrade the impact property of the joint. This is probably because the hardening volume was very limited. In addition, 316L steel part of the joint maintained much ductility and assisted the deformation of the joint during the impact test. The present study successfully demonstrated the resistance of the joint to neutron irradiation under the commercial reactor condition.

(別紙様式 3)
(Separate Form 3)

博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

論文題目　Dissimilar-metal bondings for reduced-activation ferritic/martensitic steel, oxide-dispersion-strengthened steel, and stainless steel

核融合炉ブランケットの主要構造材料として、低放射化フェライト鋼の実用化研究が進められている。また、近年、運転温度を高めて発電効率を向上させるため、高温強度を高めた酸化物分散強化鋼の開発研究も大きく進展している。Fu Haiying 氏は、この先進材料である酸化物分散強化鋼をブランケットの高温部（プラズマ側）に部分的に採用する際に不可欠となる異種材料の接合の研究に取り組んだ。また、ブランケットと接続される炉外機器の構造材料であるオーステナイトステンレス鋼と低放射化フェライト鋼の接合にも取り組み、ブランケットシステムとして成立性を示すことを目指して異材接合の研究を行った。

博士論文は、序論（１章)、実験方法（２章)、実験結果と検討（３章)、有限要素法計算による電子ビーム溶接部の変形挙動解析（４章)、および結言（５章）で構成されている。核融合原型炉の主要構造材料と考えられている低放射化フェライト鋼とその酸化物分散強化鋼の異材接合には、３次元形状の接合が可能な熱間等方圧加圧（HIP）と配管同士の接合に適した電子ビーム溶接（EBW）が適していると考え、それらの接合条件の最適化研究を行った。HIP や EBW による特性劣化の原因を探るため金属組織を分析し、これらは接合界面での脱炭、炭素の固溶を伴う相変態、及び炭化物の粗大化など、主に炭素の挙動により説明できることを示した。特に HIP では接合界面の脱炭で局所的に強度が低下することを世界で初めて発見し、そのメカニズムにもとづき、特性劣化を回復させるための焼きならし（オーステナイト化後空冷する熱処理、金属組織を微細化）と焼き戻し（オーステナイト変態開始温度以下の温度で加熱後に冷却する熱処理、延性を回復）の条件を探索し、接合強度が母材の強度以上で、かつ、母材の強度低下のない異材接合条件の特定に成功した。EBW においては、溶接金属と熱影響部に急冷によるマルテンサイト相が析出して延性が低下することを明らかにし、焼き戻し温度を適切に選ぶことによってこれらの延性を回復できること、また、さらに焼きならしを組み合わせることによって母材の硬さも回復できることを実証した。ブランケットと接続される炉外機器の構造材料であるオーステナイトステンレス鋼と低放射化フェライト鋼の異材接合には EBW を適用し、原子炉による中性子照射試験を行い、発電炉で想定される照射量においても十分な接合強度と延性を保つことを示すとともに、熱影響部の焼き戻しが十分でない場合に中性子照射による硬化が加速されることを初めて明らかにした。また、母材の強度が溶接部より低い場合は引張試験では溶接部の強度を評価できないため、有限要素法を用いて４点曲げ試験の変形挙動解析を行うことにより大きな曲げ変形を与えた時の溶接部の応力を評価し、従来よりも溶接部の強度評価の精度を向上させることに成功した。これらの成果は、低放射化フェライト鋼を主要部材とし、その酸化物分散強化鋼を高温部に使用する先進ブランケットシステムの成立に直結するもので、工学的な意義が極めて大きい。また、接合材の特性劣化とその回復メカニズムの解明や、接合強度評価手法の高精度化は、学術的にも高く評価できる。

以上のように、本研究は、高温部に耐熱性に優れた酸化物分散強化低放射化フェライト鋼を採用する先進ブランケットシステムに不可欠な異種材料の接合における最適な接合条件を詳しく調べたものであり、核融合工学として非常に価値の高い内容となっている。特に、これらの異種材料の HIP 接合は、これまでほとんど研究が行われておらず、本研究に

より強度低下のない接合条件を見いだしたことは世界的な先駆け研究として高く評価できる。低放射化フェライト鋼とその酸化物分散強化鋼、および、低放射化フェライト鋼とオーステナイトステンレス鋼の異種材料の接合において、特性劣化とその回復メカニズムを解明することにより、接合強度が母材の強度以上で、かつ、母材の強度低下のない接合条件の特定に成功したことは、博士論文として十分な価値を有すると共に核融合研究に資するものであると判断した。