氏　　　名	李　怀林
学位（専攻分野）	博士（工学）
学位記番号	総研大甲第985号
学位授与の日付	平成１８年９月２９日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第６条第１項該当
学位論文題目	Low Cycle Fatigue Properties of Reduced Activation Ferritic / Martensitic Steel (JLF-1) at Elevated Temperature
論文審査委員	主　査　教授　室賀　健夫 教授　西村　新 教授　岡村　昇一 教授　野田　信明 教授　北條　正樹（京都大学） 研究員　谷川　博康（日本原子力研究開発機構）

論文内容の要旨

One of the most important tasks in the 21th century is to develop a social system in which the environment and life on a global scale are protected. Central item to this issue is the development of economical energy sources with low emission of carbon dioxide because carbon dioxide leads to global warming and may cause more critical issue of abominable global climate. On the other hand, the supplement of fossil fuels is limited. The development of advanced energy is an important option concerning stable energy source in the century.

Among the fission, fusion, and other sources such as wind power, fusion has been actively considered as the 21st century energy source in major countries to meet the energy requirement of our society in the future, because it has potentially superior characteristics with respect to safety, environment acceptability, and resource availability. The structural integrity of fusion reactor depends on the properties of the structural materials. Thus, the development of reactor materials and power generating blanket system is a critical issue for early realization of fusion energy. Among the three materials for fusion applications—reduced activation ferritic/martensitic steel (RAF/M), V-alloy, and SiC/SiC composites, the RAF/M steel is considered as the leading candidate structural material for the first wall in fusion reactor as there exist a well-developed technology and a broad industrial experience with the ferritic/martensitic steels in fossil and nuclear energy technologies.

Low cycle fatigue (LCF) behavior of RAF/M steel at elevated temperatures is necessary to design since the cyclic plastic deformation might be expected if the combined mechanical and thermal cyclic loading of the first wall is extremely high. In addition, mechanical properties of martensitic steels are strongly related to their complex microstructure.

Thus, the objective of this research is to study the LCF behavior of a candidate structural material of the first wall, JLF-1 steel, at elevated temperatures with an engineering size specimen in vacuum. To avoid the shape, size, and environment effects, the LCF tests were carried out with engineering size (8 mm in diameter) round bar specimens in vacuum. The present research focuses on the following items:

1) Temperature effect on the relationship between fatigue life and plastic strain range.
2) Cyclic softening/hardening and the mechanism.
3) Cyclic yield stress-strain curves and its application on design.

To obtain basic information of RAF/M at elevated temperature, the tensile test was also carried out.

Tensile and LCF specimens were polished in the longitudinal direction with #1500 emery paper to remove the circumferential machining layers. The test system consisted of mechanical machine (load capacity of ±98 kN), vacuum system (~10^{-3} Pa), and induction heating system (capacity of up to 973 K). The axial displacement of the specimen was measured by a Shinko 1501-93-20 extensometer (a differential transducer with gage length of 12.5 mm and capacity of ±1 mm). Based on the temperature profile on the specimen, two thermocouples were welded in the gage length on the specimen for temperature control. One thermocouple was used for the control of the temperature and the other was to monitor the temperature during the test. The temperature difference in the two thermocouples was kept less than 3 K, which was more strictly than the requirement of ASTM standard.

Tensile tests of JLF-1 steel were carried out from room temperature (RT) to 873 K at strain rate of 0.1%/s and 0.02%/s. The strain rate does not affect yield stress, ultimate tensile strength and reduction in area as far as the tests performed in this study. Strain hardening of JLF-1 steel decreased significantly above 673 K, almost no strain hardening was observed at 873 K. With strain hardening decreased, the aspect of fracture was changed from shear type fracture below 673 K to dimple type fracture at 773 K and 873 K. Since a little strain hardening results in lower deformation resistance at 873 K, the deformation becomes larger and larger when the stress should be over the yield point.

LCF tests of JLF-1 steel were carried out in vacuum using a fully reversed push–pull strain controlled triangular wave with the strain rate of 0.1 %/s at RT, 673 K, and 873 K. The fatigue life at elevated temperature was almost as same as that at RT when the life was plotted against the total strain range. But when the life was plotted against the plastic strain range, the fatigue life curves for RT, 673K and 873 K were on different lines, which is not in agreement with the Coffin's model. The TEM images showed that dislocation structure is dependent on temperature; dislocation rearrangements keeping high density at RT, dislocation decrease to medium level at 673 K, dislocation density decrease to low level at 873 K. Loss of dislocation pile up will result in reduction of strain hardening at high temperature. So, the loss of strain hardening will be responsible for the increase of fatigue life at high temperature when plotted against the plastic strain range.

Cyclic softening was observed during LCF test at elevated temperatures in vacuum, which was strongly related to reduction of the dislocation density, formation and loss of dislocation cell structure, and increment of lath width caused by partial annihilation of original lath boundaries. The correlation of Vickers Hardness and microstructure for the present experiment is investigated to obtain mechanistic understanding on the mechanical property change such as fatigue life and cyclic softening. The cyclic stress-strain curve can be obtained from the fatigue stress-strain hysteresis curves around half life. Strain hardening decreased significantly at 873 K. The cyclic yield point was lower than the static one, especially at 873 K, that means cyclic deformation at elevated temperature will reduce the design margin. So, cyclic yield stress-strain curve of JLF-1 steel have to be applied for fatigue design and safety analysis.

In summary, this study has demonstrated that the fatigue life was dependent on temperature when plotted against the plastic strain range, which is not in agreement with the Coffin's model. The loss of strain hardening will be responsible for this phenomenon. It is also indicated that the phenomenon of cyclic softening of JLF-1 steel is a critical issue for design, which will cause the reduction in design margin significantly. The cyclic yield stress is a base for design and safety analysis. The design stress of $1/3\sigma_{UTS}$ is acceptable at 873 K in case of JLF-1.

論文審査結果の要旨

核融合炉において、核融合中性子に起因した材料の放射化は重要な問題であり、機器の保守点検、廃炉後の維持管理、材料のリサイクルなどを考慮して、いわゆる低放射化構造材料が開発されてきた。本論文で取り上げているのは、低放射化フェライト／マルテンサイト鋼であり、この材料は従来の材料に比べより高温での使用が可能である。固体ブランケット、Li-Pb や溶融塩を冷媒とするブランケットなどで使用され、高い熱効率が期待されている。ブランケット内部には冷媒が流れており、いかなる漏洩も許されない。一般に構造材料には静的な荷重と動的な荷重が作用する。特に重要な機器においては、予知しきれない地震などの過剰な荷重による低サイクル疲労挙動の把握が必要となる。日本の大学連合が開発してきた JLF-1 鋼（低放射化フェライト／マルテンサイト鋼）の高温疲労特性に関しては、これまで小型試験片を用いた研究がなされてきたが、工学的な寸法の試験片を用いた精密な検討は未だなされていないのが現状であり、設計の基礎となる高温疲労寿命線図や金属組織変化に対する転位論的考察が必要とされている。

Li Huailin 君は、この JLF-1 鋼の高温低サイクル疲労特性を研究課題とし、軸ひずみ制御高温低サイクル疲労による疲労寿命線図の作成、および疲労過程中の繰返し加工軟化機構の解明に取り組んだ。軸ひずみ制御高温疲労試験法は、試験部直径 8 mm の丸棒試験片に高温用の伸び計を取り付け、試験片がセットされている空間全体を真空にした後、高周波誘導加熱により試験片の温度を 673 K もしくは 873 K に保持し、引張ひずみと圧縮ひずみが絶対値で同じになるように、繰り返しひずみを制御しながら加えるものである。ひずみ速度を 0.1%／秒で一定とし、き裂の発生により引張応力が低下するまで同じひずみを与え続けた。この時適当な回数毎に応力・ひずみ履歴曲線を測定し、その変化を検討している。JLF-1 鋼を対象としたこのような研究は、世界で初めてなされたものである。

得られた疲労寿命線図は核融合炉内構造物の設計データベースとして非常に有用であり、今後のブランケット設計に大いに貢献するものと期待される。多くの構造材料では、塑性ひずみ範囲を変数として疲労寿命を整理すると温度の変化に無関係に一義的に表現されることが知られているが、JLF-1 鋼の場合、塑性ひずみ範囲を変数として整理すると高温での疲労寿命が低温でのそれに比べて明らかに長くなることが認められた。この原因を解明するため、Li 君は透過型電子顕微鏡（TEM）を駆使し、高温になるほど転位の集積が起こり難くなり、加工硬化が認められなくなること、そして転位の絡み合いが少なくなるため疲労寿命が長くなることを明確に示した。また、疲労過程中に繰返し加工軟化が生じる原因として、転位密度の低下とマルテンサイトラス幅の増加が考えられることを示した。さらに、Li 君は、疲労過程中の硬さの変化に注目し、硬さの変化量は、転位密度の変化量、転位セルの大きさの変化量およびマルテンサイトラス幅の変化量によって表されることを示した。転位セルの寸法変化やマルテンサイトラス幅の変化に注目して繰返し加工軟化や硬さ変化を実験的に説明した研究はこれまでほとんどなされておらず、これらの研究成果は今後の高温材料開発の高度化に向けた指針となる。また、繰返し応力・ひずみ線図と静的な応力・ひずみ線図の関係を具体的に示し、設計許容度に対する繰返し応力・

ひずみ線図の重要性を指摘した。
以上本研究は、核融合炉用の構造材料として期待される低放射化フェライト／マルテンサイト鋼（JLF-1 鋼）の高温低サイクル疲労特性を明らかにするとともに、疲労過程中の金属組織の変化を詳細に検討し、金属組織学および金属物理学の観点より繰り返し加工軟化および疲労寿命の温度依存性について考察を加えたものである。これらの成果は核融合炉ブランケット用構造材料開発研究に大きく寄与するとともに、学術的にも意義あるものと認められる。以上により、本論文は学位論文として十分価値があると判断した。