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REVIEW

Fusion power: a challenge for materials science

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The selection and design of materials that will withstand the extreme conditions of a fusion power plant has been described as one of the greatest materials science challenges in history. The high particle flux, high thermal load, thermal mechanical stress and the production of transmutation elements combine to produce a uniquely hostile environment. In this paper, the materials favoured for the diverse roles in a fusion power plant are discussed, along with the experimental and modelling techniques that are used to advance the understanding of radiation damage in materials. Areas where further research is necessary are highlighted.

Keywords: fusion; energy materials; materials science

1. Introduction

As concerns about climate change intensify and oil and coal supplies become depleted, nuclear power will become an increasingly favoured option for large-scale power generation. Nuclear power is not without its opponents, however. The common criticisms are centred on safety issues, the disposal of radioactive waste and the limited supply of raw materials such as uranium. While there may be some grounds for concern about these issues for fission power, fusion should offer a source of safe, clean power generation, with a plentiful supply of raw materials. There are only a few grams of fuel in the reactor vessel, which is sufficient for a few seconds of burn; therefore, a runaway reaction is not possible. The materials close to the fusion reaction will become radioactive but, with careful materials selection, these materials will have a short half-life; therefore, the waste disposal problems will be minimal (Llewellyn Smith & Ward 2008).

Significant scientific and engineering advances will, however, be necessary before the fusion reaction can be used as a source of commercial power generation. These challenges can be loosely divided into three categories: plasma control, power extraction and material selection. The first is concerned with plasma

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ignition and control. In order to ignite a deuterium–tritium (D–T) plasma, temperatures of around 100 million degrees Celsius are necessary and the plasma must be contained away from the reactor walls. Plasmas are ignited on a regular basis at the Joint European Torus (JET), and other fusion facilities, but the energy required to heat the plasma is currently greater than the energy produced by the fusion reaction. The international tokamak experimental reactor (ITER) experiment is designed to cross this fundamental threshold and produce significantly more energy than it consumes. The energetic alpha particles produced in the fusion reaction will heat the plasma and result in a self-sustained reaction. The plasma must be controlled to limit the number of energetic particles bombarding the walls of the vessel and the configuration of the magnetic field must be such that the relatively cool alpha particles are diverted out of the plasma to the exhaust region round the base of the vessel.

Once it is established that a self-sustained fusion reaction is feasible, the next challenge will be to design a system that will both capture the power generated by the reaction and breed tritium from the lithium raw material. Tritium has a relatively short half-life and natural supplies are scarce, so the commercial power generation will be viable only if tritium can be produced *in situ*, by using the fusion neutrons to activate lithium. Both functions, energy capture and tritium breeding, will be carried out by the blanket system, which will be located behind the first wall of the reactor vessel. There are a number of proposed blanket designs but the technology is currently largely unproved. The ITER experiment will have a facility for testing blanket modules, which will help to establish the most efficient and effective design.

The third challenge is the main focus for this paper. It has been argued that the design of a fusion power station represents the greatest materials development challenge in history (Zinkle 2005). Fusion materials must withstand high temperatures, high levels of radiation damage, high production rates of transmutation elements and high thermo-mechanical stresses. There is clearly a strong overlap with materials research for fission power; however, fusion materials present additional challenges. The first of these is the copious amount of helium that is produced, both in the D–T fusion reaction and by transmutation reactions in the structure. Helium bubbles formed at vacancy clusters and grain boundaries cause swelling and embrittlement. The second effect that is unique to fusion reactors is associated with the 14 MeV neutron produced by the fusion reaction. This extremely high-energy particle penetrates deep into the structure and collides with the atoms, creating a high number of defects in the material. It is the accumulation of this damage in structural and diagnostic materials that is one of the primary concerns for power plant design.

The ITER experiment will link current plasma experiments to a demonstration power plant by establishing the feasibility of a self-sustained plasma burn. The materials in the ITER design were selected for optimum plasma conditions and, as the total neutron fluence and helium production will be relatively low, the chosen materials are expected to survive for the lifetime of the experiment. The conditions in a power plant will, however, be much more demanding as the neutron fluence and heat loads will be increased by an order of magnitude and the operating temperature will be higher. In this paper, we review the conditions that materials must withstand for various functions in a fusion power plant and the materials that are currently thought to be best suited to the roles. We discuss the experiments and modelling techniques that contribute to the understanding of radiation damage and its effect on the mechanical and functional properties of the materials.

2. The challenges of material selection

A schematic representation of a fusion power plant is shown in figure 1. The outer region represents the superconducting magnets that will confine the plasma. The intermediate region is the vacuum vessel and the inner region is the first wall which includes the blanket system that will breed neutrons and extract power. The materials experiencing the harshest environments in fusion power plants are those that are contained within the vacuum vessel and they can be broadly classified into three types. The conditions experienced, and the issues to be addressed, by each class are diverse. In this section, we discuss the issues and the most promising candidate materials for the first wall materials, plasma-facing materials and diagnostic materials.

(*a*) *First wall materials*

The first wall of a fusion power plant must contain the integrated blanket that plays the dual role of breeding the tritium fuel and capturing the useful power from the fusion reaction. Efficient designs would operate at high temperatures; therefore, good creep resistance and high-temperature strength are important criteria. First wall materials will be subjected to high neutron loads (approx. 8×10^{14} neutrons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) and they will experience up to 120 dpa (displacements per atom) over the lifetime of a power plant (Ehrlich *et al.* 2000). The neutron-generated radiation damage, and its effect on the mechanical properties, will be a significant issue. Residual defects created by each radiation event evolve over time and form small clusters or dislocation loops, which will eventually reduce the fracture toughness of the material. Helium atoms, produced by the fusion reaction and by the decay of transmutation elements, become trapped in vacancy clusters, and this will cause swelling and embrittlement. The neutrons may also induce segregation. Alloy components in metastable solution could be driven towards equilibrium by radiation-enhanced diffusion, with a corresponding degradation in properties (Bloom *et al.* 2007). Neutron activation of certain elements produces long-lived radionuclides, and alloy concentrations of such elements must be kept to a minimum to minimize waste disposal issues.

The main contenders for first wall structural materials are reduced activation ferritic/martensitic (RAFM) steel, vanadium alloys and $\mathrm{SiC_{fibre}/SiC}$ composite materials (Ehrlich *et al.* 2000; Laesser *et al.* 2007). Currently ferritic/martensitic steel is the favoured option, not least because of the vast amount of technological experience available. Austenitic steels have been ruled out because of the unfavourable radiation resistance of *fcc* metals and high Ni content. The requirement for only short half-life radioactive waste means that Ni and other high-activation elements such as Ti and Co are undesirable and this has resulted in the development of a range of reduced activation steels targeted at fusion applications (Klueh 2005). Embrittlement and high-temperature strength remain open issues, as ferritic steels rapidly lose strength at temperatures higher that

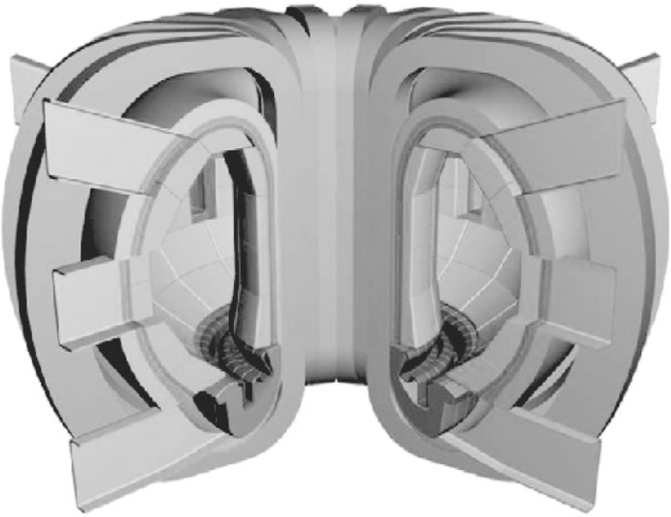

Figure 1. Schematic representation of a fusion power plant design. The superconducting magnets are the outer layer. The vacuum vessel, the first wall and the blanket are inside the vacuum vessel and the dark region round the base of the tokamak represents the divertor.

550°C. Experimental alloys, such as oxide dispersion strengthened (ODS) steel, in which nanoscale oxide particles increase the high-temperature strength, are being developed. The insoluble particles play the dual role of defect sinks and dislocation barriers. Preliminary results on the high-temperature stability and radiation resistance of the oxide nanoparticles are encouraging (Odette *et al.* 2008).

Vanadium alloys offer some advantages over ferritic/martensitic steels (Bloom *et al.* 2004) in terms of their superior high-temperature performance. There is evidence that operating temperatures up to 700°C may be possible, which is higher than that anticipated for ODS steels. Vanadium alloys are the only low-activation alloys that would be compatible with liquid Li; therefore, their use would be essential if the liquid Li coolant option was preferred. The disadvantages of vanadium include the lack of a production infrastructure and the relatively immature joining technology.

SiC/SiC composites have attracted considerable attention for first wall materials, mainly because of their excellent high-temperature strength (Nozawa *et al.* 2009). SiC is a brittle material, but the fracture toughness of the composite can be improved by tailoring the fibre, matrix and the interphase material. The performance of the composite, particularly the fibre matrix interface, under neutron irradiation is still an open issue, however. As with vanadium alloys, there is concern about the lack of manufacturing infrastructure, joining technology and fabrication costs.

Table 1 summarizes the primary candidates for first wall structural materials. Early demonstration power plants are likely to use ferritic/martensitic steels, with the result that the operating temperature will be somewhat restricted. Research into alternative materials that will maintain strength to higher temperatures will continue for future generation thermo-nuclear power plants.

Table 1. The leading contenders for first wall structural materials and the main advantages and disadvantages.

material	advantages	disadvantages
RAFM steel	mature technology	poor high-temperature strength, irradiation hardening
V alloys	compatible with Li, good high-temperature strength	immature technology
SiC_{fibre}/SiC composite	good high-temperature strength	immature technology, brittle

(*b*) *Plasma-facing materials*

Additional challenges need to be confronted for the selection of the materials that face the plasma directly in a fusion reactor. Not only does consideration have to be given to the effect of the plasma on the material, but the effect of the material on the plasma is also a concern (Federici *et al.* 2001; Samm 2008). The requirements of the effect on the material and the effect on the plasma are, in fact, somewhat contradictory. Plasma-facing materials experience high fluxes of both neutral and charged particles that escape from the plasma and these sputter atoms from the surface of the wall. The sputtered atoms may enter the plasma and result in radiative cooling. Low atomic weight (low Z) materials require less energy for ionization and these are, therefore, the preferred option for plasma-facing materials, hence the choice of beryllium for the coating of the first wall in ITER. Low Z metals have low melting points (low binding energies) and high erosion rates; therefore, from the materials perspective, high Z metals are the preferred option. The high erosion rate and high toxicity of beryllium mean that it is unlikely to be the material of choice for a power plant design (Cottrell 2006). Tungsten, because of its high melting temperature and thermal conductivity, may be a viable alternative (Neu 2006).

The role of the magnetic field in a tokamak is to confine the plasma and prevent it from coming into contact with the vessel walls. However, in a burning plasma, it is necessary to remove the excess energy and fusion products (alpha particles) from the vessel. The magnetic field lines must come into contact with the vessel wall; in ITER, this is done using the X configuration such that the outer (open) field lines contact the wall round the base of the tokamak. Particles escaping the plasma are diverted along the field lines and contact the wall in a region known as the divertor. Divertor materials experience the harshest conditions of all the materials in a fusion reactor in terms of both the heat load, which is comparable to rocket nozzles (Odette *et al.* 2008), and particle bombardment.

Early experiments used metals as plasma-facing materials, but graphite was found to increase the plasma temperature dramatically because of its efficient radiation properties (Linke 2006). Graphite also has high thermal conductivity and low Z, both of which make it a suitable divertor material. Graphite does, however, have a major disadvantage—its high reactivity with hydrogen (Roth *et al.* 2005). Low-energy hydrogen that comes into contact with the divertor reacts with surface carbon to form volatile hydrocarbons that are re-deposited

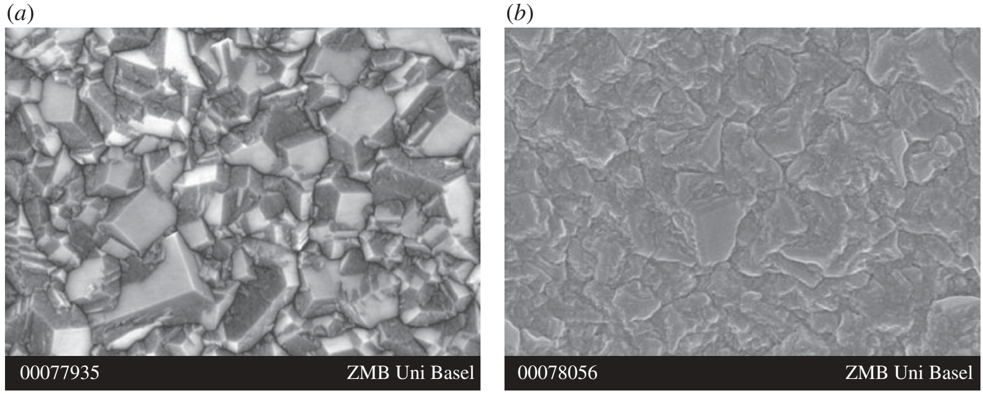

Figure 2. Scanning electron microscopy micrographs of a microcrystalline chemical vapour deposition (CVD) diamond film on a Mo substrate (Heriot-Watt University) (*a*) before and (*b*) after exposure to a high-density H plasma in the Pilot PSI plasma simulator. The surface grains are rounded and eroded but overall the coating was not heavily affected. Scale bars, (*a*,*b*) 500 nm.

in a different part of the vessel. This would be a major problem for the tritium inventory because of both resource and safety issues. Tritium is a scarce resource and it is highly radioactive; therefore, it is desirable that it should be contained in the plasma. Carbon remains in the ITER design, in the form of carbon fibre-reinforced carbon (CFC), only at the strike points of the divertor. The remainder of the divertor uses tungsten as a plasma-facing material, which is favoured because of its high melting temperature and thermal conductivity.

Diamond has been suggested as an alternative to graphitic carbon as a possible divertor material (Stoneham *et al.* 2004). Its exceptional thermal conductivity would be favourable for high thermal loads and its strong bonding should decrease its susceptibility to chemical erosion by hydrogen. Tiles or components made from a range of materials, including tungsten or graphite, could be coated by microcrystalline or nanocrystalline diamond to produce a protective coating. Preliminary experiments on diamond-coated Mo, Si and graphite tiles have produced encouraging results (Porro *et al.* 2009*a*,*b*) and further experiments are planned. Some degree of arcing was detected but this could be eliminated by doping with boron to increase the electrical conductivity. The microstructure of a microcrystalline diamond film, before and after exposure to a high-density H plasma, is shown in figure 2. Graphitization and amorphization, owing to radiation damage and high thermal loads, may negate some of the advantage of using diamond, but again doping with selected elements could be used to minimize this effect. We are investigating graphitization and amorphization of diamond under high thermal loads using classical molecular dynamics. Preliminary results demonstrate that passivation by H has a strong stabilizing effect (figure 3).

In summary, the plasma-facing materials in general and the divertor in particular present the greatest challenge for materials selection in a fusion power plant. Table 2 summarizes the current contenders, but further materials development will be required for this exceptionally challenging application.

(*a*)

(*b*)

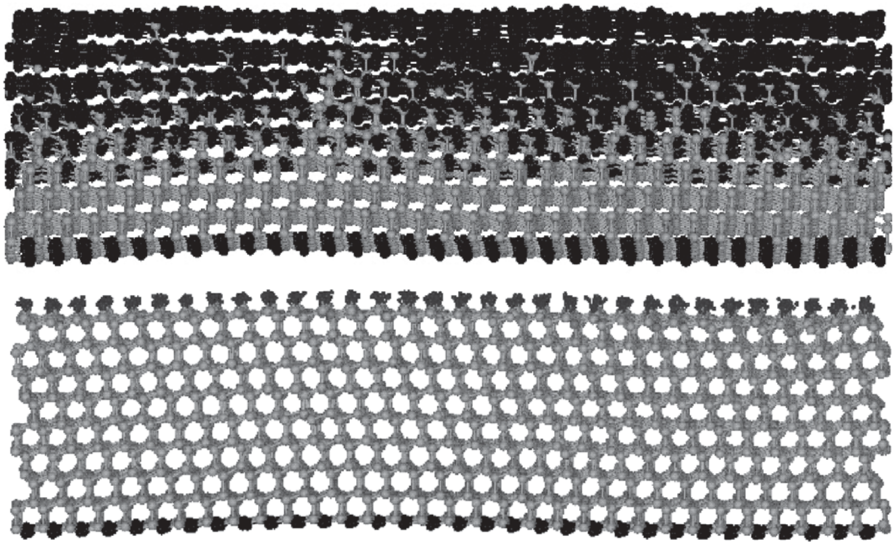

Figure 3. Classical molecular dynamics (MD) models of the structures of (*a*) a clean and (*b*) an H terminated (111) slab (15552 atoms, reactive empirical bond order (REBO) interatomic potentials (Brenner *et al.* 2002)) of diamond, after heating from 300 K to 1760 K at a rate of 38 K ps^{-1}. The bottom 2.5 layers are fixed to simulate bulk termination. C atoms are shown in mid-grey (sp3) and black (sp2) and H atoms are shown in light grey. The H termination stabilizes the surface against graphitization.

Table 2. The leading contenders for plasma-facing materials and their main advantages and disadvantages.

material	advantages	disadvantages
beryllium	low Z, getters O	low Tm, toxic, high physical sputtering yield, brittle
tungsten	high thermal conductivity, high Tm, low sputtering yield	high Z, brittle
CFC	low Z, high thermal conductivity, high Tm	high chemical sputtering, brittle, dust generation
diamond	low Z, high thermal conductivity, high Tm	brittle, dust generation, possible amorphization, poor conductor

(*c*) *Diagnostic materials*

The diagnostic set for burning plasma experiments must cope with the harsh environment of high-energy neutron and gamma flux, which penetrate well beyond the first wall. The materials used in the diagnostic set need to maintain not only mechanical strength but also a number of other properties such as electrical and thermal conductivity, dielectric loss and optical characteristics (Hodgson 2002). Some commonly used materials are unsuitable for high-dose environments because of their poor radiation resistance; therefore, substitute materials must be used. Examples include polymers for cable insulation, alkali halides for scintillators, SiO for mirror coatings and mica for bolometer substrates (Gonzalez & Hodgson 2003).

The degradation of optical properties is the primary concern for mirrors, windows, lenses and optical fibres. Candidate materials include SiO_2 or Al_2O_3; however, the creation of defects by radiation produces defect states in the band gap and degrades absorption properties. The high-power radio-frequency window for electron cyclotron resonant heating needs to have high mechanical strength, low dielectric loss and high thermal conductivity. Alumina is a strong candidate but it is, in fact, only viable at low temperatures and low neutron fluence. Si has low dielectric loss, but the extended lifetime of electronic excitations increases the loss to unacceptable levels under irradiation. High-quality CVD diamond films have been produced that have low loss and high thermal conductivity (Ibarra & Hodgson 2004). The high number of defect sites ensures that the excited states are short-lived and so the dielectric loss is unaffected by radiation.

The resistivity of electrical insulators is strongly reduced by radiation that excites electrons to the conduction band; however, this radiation-induced conductivity decays rapidly when the radiation source is removed (Pells 1991). In contrast, radiation-induced electrical degradation (RIED) permanently enhances the electrical conductivity of wide band-gap materials. RIED is caused by a synergy between displacement damage and electronic excitation. Excited electrons or holes are trapped in defects, such as dislocations, that have been created by the displacement damage (Pells & Hodgson 1995). Relatively small electric fields may modify the damage process, in which case the material degradation will be sensitive to the strength of the local electric field (Hodgson & Morono 2000).

In summary, materials used for diagnostics in a burning plasma environment face severe challenges because of the synergy between the structural defects and the electronic defects created by radiation. The electronic and optical properties will be strongly affected by trapped electronic excitations, resulting in a severe degradation in device performance.

3. Testing materials

The ability to test the performance of materials in a burning plasma environment is hampered by the unavailability of an experimental facility with a high-flux source of 14 MeV neutrons. Most experimental results on radiation have been obtained by irradiation with ions with a range of energies or by high-energy electrons. This has been largely successful and a considerable knowledge base on radiation effects on both metals and insulators has been developed. There is some concern about the extrapolation of these results to damage caused by high-dose, high-energy neutrons not least because the activation, and consequent gas (He, H) production, of the nuclei is absent in such facilities.

The current facilities for testing the effects of neutron irradiation are summarized by Stoneham *et al.* (2004). They generally suffer from the disadvantage that the maximum recoil energies are well below that expected from 14 MeV neutrons and the gas production rate is around 50 times too low. Test facilities are planned that will be able to reproduce damage and the gas production rate comparable to a fusion power plant. One facility, known as the International Fusion Material Irradiation Facility (IFMIF), will use a design in which a lithium target is bombarded with deuterium nuclei. It will generate 14 MeV neutrons with a flux of 10^{17} neutrons s^{-1}. IFMIF aims to produce damage of 20–50 dpa yr^{-1}, which is comparable to fusion power plant conditions (Garin & Sugimoto 2008). The facility is complex, however, and the concepts of the design have yet to be fully validated.

Designs for a component test facility, based on a spherical tokamak, have also been proposed (Voss *et al.* 2008). The facility would aim to test large components, such as blanket modules, under reactor relevant conditions. Results from these tests would complement and extend the information obtained from the IFMIF facility. The facility could be based on a small spherical tokamak and would burn a D–T plasma to produce 14 MeV neutrons. Such a facility would accelerate the design of the first demonstration power plant by enabling the evaluation of different blanket designs.

4. Materials modelling

The considerable difficulties involved with testing materials in fusion relevant conditions have accentuated the role of materials modelling in this field. Modelling is not without its challenges, however, not least because of the range of time and length scales over which radiation damage occurs. A high-energy particle or ion moving within a material loses energy by collisions with the atoms, resulting in local disorder or melting. As the excess energy diffuses through the material, the disordered region recrystallizes, leaving behind a number of defect clusters. The time scale of the energy dispersal is a few tens of picoseconds, which is typical of the time scale that can be modelled using molecular dynamics simulations. The defect structure continues to evolve over much longer time scales (weeks or even years) as the defects migrate, cluster and interact with the microstructure of the material. Such radiation-induced microstructure evolution is responsible for the well-known radiation-enhanced hardening and swelling that degrade the performance of metals that have been subjected to a radiation environment.

(*a*) Ab initio *modelling*

The range of length and time scales require a range of modelling techniques for a complete description of radiation damage. On the shortest length/time scales density functional theory (DFT) can be used to calculate defect formation and migration energies. Formation energies can be used as fitting parameters for interatomic potentials (Derlet *et al.* 2007) and migration energies are used as input for long time-scale models such as Monte Carlo and rate theory.

(*b*) *Cascade simulations*

On the next level up molecular dynamics (MD), in the form of cascade simulations, is used to model the structural evolution for the time period of a few tens of picoseconds following a radiation event. In a cascade, the simulation is initiated with one atom, the primary knock-on atom (PKA), moving at a high velocity to model the impact with a radiation particle. The PKA rapidly distributes its energy to the surrounding atoms, resulting in a region of dynamic disorder sometimes referred to as the thermal spike. The material recrystallizes as the energy is dispersed but some defects remain, with the residual vacancies located near the core of the cascade. Fast interstitial migration (via channelling and replacement collision sequences) separates vacancies and interstitials and inhibits defect recombination. The number of defects stabilizes after a few picoseconds as the lattice temperature returns to the ambient value. The residual defect distribution can be used as input to long time-scale methods.

Cascade simulations have made significant contributions to the understanding of radiation damage in both metallic and insulating materials over the years; however, they have a number of limitations. The first of these is that the energy of the radiation event that can be modelled depends on the size of the simulation cell, which in practice means that simulations are generally restricted to PKA energies of less than 100 keV. The maximum PKA energy for a 14 MeV neutron in Fe is 1 MeV; therefore, the full effects of fusion neutrons cannot be modelled directly. The second limitation involves the interatomic potentials that are used to model the materials. Using interatomic potentials to represent the interactions between atoms in a material is, necessarily, a severe approximation as the electronic degrees of freedom are effectively integrated out. Some material properties may be well represented with a particular potential, but the challenge of developing potentials that will reproduce a wide range of properties is well documented (Nordlund & Dudarev 2008).

Classical interatomic potentials give a poor description of radiation events that result in a high level of electronic excitation, such as radiation by high-energy ions, electrons or lasers. Several techniques have been employed to address this issue in metals. These range from a representation of energy loss to electronic excitations by a friction term in the equations of motion (Nordlund *et al.* 1998) to a high-level quantum mechanical Ehrenfest methodology (le Page *et al.* 2009). At an intermediate level, the electronic energy is represented by a local electronic temperature and energy is exchanged between the electrons and the lattice at each simulation step (Duffy & Rutherford 2007). Including the electronic excitations has been found to have a significant effect on the residual damage for both cascade simulations (Rutherford & Duffy 2007) and sputtering simulations (Khakshouri & Duffy 2009) in metals.

Insulating materials present particular challenges for radiation damage modelling because of the complex interactions between electronically excited states and the lattice defects produced by low-energy ion irradiation. The RIED effect discussed in §2*c* is a clear example. Ionizing radiation can either enhance or reduce defect accumulation rates (Zinkle *et al.* 2002). The excited electrons–hole pairs diffuse in the lattice, either as independent entities or as bound pairs, and recombination may occur either radiatively, when a photon is emitted, or non-radiatively. Non-radiative decay results in the transfer of energy to the lattice, either as phonons, resulting in lattice heating, or as defects. Mobile electrons and holes may get trapped at pre-existing defects (vacancies and interstitials) and alter the activation energies for diffusion, which will affect both clustering and annealing. The challenge is to include these diverse effects in MD simulations by coupling a model for the electronic excitations to the atomistic model, in a similar way to that done for metals (Duffy & Rutherford 2007). The development of such a coupled model is in progress.

(c) Long time-scale methods

MD simulations can model only the first few nanoseconds following a radiation event but the results from these simulations can be used, along with migration energies determined from DFT calculations, to extrapolate to longer times using object kinetic Monte Carlo (OKMC). OKMC can evolve microstructures over time scales of the order of years, by considering a range of objects (e.g. vacancies, interstitials and solutes) and events (e.g. defect creation, emission, trapping and aggregation) and associating each possible event with a rate (Domain *et al.* 2004). The reliability of the model is limited by the accuracy with which the large number of events that could occur in a real material can be described.

An alternative method for modelling long time-scale radiation damage evolution is mean field rate theory (MFRT). In this procedure, an initial distribution of defects and defect clusters is assumed and the distribution is evolved using a set of master equations. Again the rates of defect generation, emission, aggregation and annihilation must be known for a complete model. Stoller *et al.* (2008) have compared OKMC and MFRT for equivalent simulations and they found that OKMC gave more reliable results when there was spatial correlation in the initial defect distribution, because MFRT contains no spatial information. The statistical nature of OKMC implies, however, that it is more reliable for high defect numbers (high dose rates and low temperatures) and extrapolation to reactor lifetimes with realistic dose rates is challenging.

In summary, the rapid increase in computer power and the development of novel modelling techniques have resulted in the rapid advancement of the understanding of radiation damage processes. Nevertheless, predictive modelling for real alloys, with complex microstructures, remains beyond our current capabilities. Further research is needed at a fundamental level on atomic interactions and migration under non-equilibrium conditions, and new techniques to include these effects in long time-scale microstructure evolution are required. This is particularly necessary for insulating and semiconducting materials, where the synergy between nuclear and electronic defects is complex and its effects are significant for the functional properties.

5. Innovative materials design

The challenges for materials in their various roles in fusion reactors are such that it will be necessary to design new innovative materials for some applications. Stoneham *et al.* (2004) suggest that composite materials could be designed in which the components have different functions. One example of such a material is ODS steel, which was discussed in §2. Such steels use insoluble oxide nanoparticles to increase the high-temperature strength and the oxide/metal interface may also play the role of a defect sink. Interfaces are known to play a dominant role in radiation resistance, with Cu/Nb interlayer materials as a prime example. In these materials, the high mixing energy between the two components results in the rapid annealing of defects. SiC has attracted interest as a fusion material because of its strength, high-temperature performance and high thermal conductivity. There is a possibility that it could be used as a fibre reinforcement to improve the high-temperature properties of Cu and also as a coating for carbon to reduce the susceptibility to chemical erosion (Zhang *et al.* 2007).

Innovative manufacturing and joining techniques will be required for fusion components, particularly for materials that will perform more than one function. One example is a copper heat sink that is coated with tungsten for improved plasma-facing performance. The thermal expansion mismatch between the two materials would result in severe interfacial stresses under thermal loads, causing cracking and delamination. Functionally graded materials, in which there is a gradual transition from one material to the other, would reduce or eliminate such stresses. Innovative techniques, such as plasma infiltration welding and resistance sintering, have been used for W coated Cu for a divertor assembly (Zhou *et al.* 2007).

6. Outlook

The challenges involved in designing materials for an economically viable fusion power plant are formidable, but none of the perceived obstacles should be insurmountable. The mood remains optimistic that economically viable fusion power will help to alleviate the approaching energy crisis (Llewellyn Smith & Ward 2008). The development of new materials requires a sound understanding of the underlying materials science issues and intense materials engineering research to develop the necessary fabrication and joining techniques. A concentrated research effort, using the latest tools for modelling, testing and manufacturing materials, will be required, with a focus both on the fundamental understanding of the response of material properties to radiation damage and on the real engineering issues. New material combinations (composites and alloys) will almost certainly be required for materials to fulfil their diverse roles in the uniquely harsh environment of a fusion power plant.

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