Object kinetic Monte Carlo methods applied to modeling radiation effects in materials

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Abstract

The object kinetic Monte Carlo (OKMC) method has proven to be an excellent tool to better understand microstructure evolution in irradiated materials, from metals to semiconductors. Its most valuable capability is that it provides a way to connect parameters obtained from fundamental models, such as first principles calculations, to experimental observations by expanding simulated time and length scales. However, the OKMC method has many limitations that pose questions on its predictive capabilities and an important effort is taking place to improve the model. In this review, first we describe the object kinetic Monte Carlo methodology, then a few examples are presented in the field of radiation damage of metals and the limitations of the method and its applicability discussed. To conclude, an outlook on the future of this computational model is given.

Keywords: Kinetic Monte Carlo, radiation damage, metals

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1. Introduction

Irradiation of materials can result in defects that alter their mechanical, electrical, thermal and/or magnetic properties. In some cases, irradiation is the means to tailor the properties, as in the case of ion implantation of semiconductors [1]. In other cases, defects are an unavoidable effect that act in detriment of material properties, as in systems exposed to high radiation levels in nuclear reactors [2, 3]. With the advance of nanotechnology, focused ion beams are used to fabricate nanoscale features [4] and questions still remain as to the effect of the radiation damage produced by this technique [5]. Understanding the phenomena behind defect production and defect evolution is key in all these different applications, either to select the most appropriate material, such as in the case of nuclear applications, or to improve the technique, as in ion implantation of semiconductors or focused ion beams.

All these different applications and experimental conditions have something in common: defects are produced in a time scale of picoseconds and are atomic scale in size, giving rise to out-of-equilibrium phenomena that can evolve over much longer time and length scales until reaching a steady-state. Therefore, this complex system cannot be tackled by a single simulation model and a multiscale approach must be used [6]. The initial damage produced by energetic particles within the picosecond time scale can be modeled using binary collision approximation methods together with molecular dynamics simulations with empirical potentials, as discussed elsewhere in this special issue. The number of defects produced as well as their spatial distribution and configuration can be obtained from these calculations.This information is crucial for the subsequent microstructure evolution, as we will show in a few examples in this review.

Object kinetic Monte Carlo (OKMC) is a computational method able to extend the time and length scale of molecular dynamics simulations to times and sizes that are comparable to experimental observations. For example, if we consider that the dose rate for ion implantation is on the order of $5x10^{10}$ ions/cm^2/s (see for example conditions in experiments performed in Jannus [7]), and that the area in an OKMC calculation can be up to (1 micron)^2, then the average time between two ions during ion implantation should be on the order of milliseconds. Molecular dynamics alone cannot easily access time scales of milliseconds since the time step is on the order of femtoseconds.,Unlike molecular dynamics simulations, in OKMC the vibrations of each atom around its equilibrium position is not modeled, and only the rare events are followed. However,there is no unambiguous method to select these processes and it is to the discretion of the modeler to decide which processes must be included and their probabilities known This is one of the limitations of the OKMC technique. Once all the probabilities of all the possible events are known, the algorithm evolves the system according to these probabilities until the final conditions are met, either total simulated time or total irradiation dose. Results can be directly compared to experimental observations such as transmission electron microscopy (TEM), positron annihilation experiments (PAS), small angle neutron scattering (SANS) or atom probe tomography (APT). These experimental methods provide information about defect concentration with dose, defect sizes and character. Contrasting the results of the calculations with different experimental observations is necessary to verify the reliability of the model considered.

In the following we will describe the OKMC algorithm, and briefly two related Monte Carlo methods, the so-called event kinetic Monte Carlo and the first-passage kinetic Monte Carlo. Several examples are presented, focused on the influence of the initial damage distribution

obtained from molecular dynamics with empirical potentials on microstructure evolution in the case of irradiated metals.

2. Methodology

The main algorithm of all Monte Carlo methods is based on a stochastic component. Consequently, there is a wide variety of algorithms under the name Monte Carlo and used for very different applications from materials modelling to risk assessment in finance [8]. The first Monte Carlo method is attributed to Ulam and Metropolis, developed while working at the Los Alamos National Laboratory during the Manhattan project [9]. See references [10, 11] for the history of this development. In the field of defects, the first simulations were done a few years later by Beeler [12], followed by those of Besco [13] and Doran [14] applied to study short-term annealing of defects in f.c.c. and b.c.c. materials.

The Monte Carlo method that will be discussed here follows the kinetics of a series of events with known probabilities of occurrence, hence its name kinetic Monte Carlo (KMC). It was first used in the field of radiation damage by H. Heinisch in the early 90's [15] and since then it has been applied to different metals, particularly iron, iron alloys [16, -20] and tungsten [21, 22], to name a few. In the case of radiation effects events are related to migration of defects, dissociation of defect clusters or interaction between different types of defects among themselves or with the existing microstructure. These are slow processes or rare events that cannot be followed with atomistic methods like molecular dynamics, where time scales are typically tens of nanoseconds, as mentioned above. In KMC, once all the different types events and event rates are known, the system evolves according to those rates, and different algorithms can be used for evolving the time. Object kinetic Monte Carlo (OKMC) models use the Bortz-Kalos-Liebowitz (BKL) algorithm (also called residence time algorithm) to evolve time [23]. In the OKMC the total rate for all possible events is calculated as:

$$R = \sum_{i=1}^{e} \Gamma_i N_i \qquad (1)$$

where *e* is the total number of possible events, Γ is the probability of occurrence of a particular event *i* and *N* is the total number of objects that can undergo event *i*. Once the total rate R is calculated, a random number selected between 0 and R will determine which event will occur. In this manner, the event is selected randomly but with the appropriate weight according to its probability of occurrence. Once the event is picked, the simulation time is updated, increasing the time by a time increment, Δt, that is inversely proportional to the total rate:

$$\Delta t = \frac{-\log \xi}{R} \qquad (2)$$

Often, the time increment is multiplied by the logarithm of a random number, ξ, between 0 and 1, to ensure that a Poisson distribution of time is achieved.

After selecting the event, an object that can realize the event is picked randomly. Actions associated to the event are then computed and the system is updated accordingly. Note that all different processes must be independent from each other, that is, the rates only depend

on the state of the system and not on the previous events. For example, in the case we are interested in, radiation damage, an event could be the migration of a self-interstitial atom. The event in this case is the migration and the object the self-interstitial. One self-interstitial is then selected randomly from all those existing in the system and displaced to a new location. In the case of an off-lattice kinetic Monte Carlo, the displacement is a fixed distance, usually taken between first and second nearest neighbours distance. Once the self-interstitial has been displaced, the algorithm evaluates the new environment of that object and performs the necessary actions. For example, if the self-interstitial is located within the capture radius of another defect, the interaction and reaction between both objects must take place, therefore changing the defect distribution and configuration. One possibility in this example is that the self-interstitial moves to a location within the capture radius of a vacancy and consequently these two defects cancel each other. The self-interstitial could also move within the capture radius of another self-interstitial and a di-interstitial would be created. Much of the simulation time is, in fact, spent in the latter part of the calculation. This also implies that at every time step, the total rate must be recalculated since the number of objects for each event could, in principle, have changed. Figure 1 shows schematically the different steps in a general object kinetic Monte Carlo calculation.

The aforementioned algorithm is, however, not the only possible method for selecting events in a kinetic Monte Carlo model. A different approach is used in the so-called Event kinetic Monte Carlo [24, 25] and first-passage kinetic Monte Carlo (FPKMC) [26]. Here, the time associated to every possible event (time delay) is first calculated and the event selected is that with the shortest time delay. The selected event is then performed, taking care of all the associated changes, as explained above, and all the new time delays have to be calculated. The time in this case advances by the delay time of the event picked. This algorithm is used in codes such as JERK [25, 27] and has been used very successfully to compute the electrical resistivity of irradiated iron (Fe) [16] and Fe in the presence of impurities such as carbon [28]. In the EKMC method some approximations are made in order to calculate the delay time for events such as the interaction between two neighbouring objects. For more details on EKMC see references [25, 27-29].

A more general method has been developed by Opplestrup et al [26] named first-passage kinetic Monte Carlo (FPKMC). In this method, as in the EKMC algorithm, the event selected is the one that would occur in the shortest time from all possible events. However, FPKMC lacks the approximations included in EKMC. In FPKMC, each object is surrounded by a “protective domain”, that is a volume where no other objects can be found. When an object is selected it is moved to the edge of that domain. This approach gives rise to a tremendous computational gain with respect to OKMC since many small jumps, that would have to be done in OKMC where the jump distance is fixed, are automatically avoided in FPKMC. However, the efficiency of FPKMC decreases significantly with respect to OKMC with increasing number of particles , since for each step, the time delays associated to all objects have to be calculated. Some applications and comparisons between FPKMC and OKMC can be found in [30].

The key parameters in KMC (either OKMC, EKMC or FPKMC) are the probabilities of the events in our system. Transition state theory (TST) can be used to obtain the rates between two different states [31]. For an extended description of TST and KMC see the review by A. Voter [32]. The transition rates are generally obtained from energy barriers between two different states of the system. Models such as density functional theory (DFT) or others less accurate, like calculations using empirical potentials, can be used to obtain these barriers. Details of these calculations can be found in other articles of this special issue.

Once the activation energy is known, the rate for the event, Γ_i, can be obtained assuming an Arrhenius dependence, if the harmonic approximation is used within transition state theory (see review by Voter for further details [32]):

$$\Gamma_i = \Gamma_{i0} \exp\left(-E_a / KT\right) \qquad (3)$$

where Γ_{i0} is the jump or attempt frequency, E_a is the activation energy for that particular event, K is Boltzmann's constant and T is the temperature. The accuracy of the method depends on the accuracy of the values of the different rates and on the selected events and interactions to describe the system. How well this model reproduces the system we are interested in can only be assessed through extensive comparisons with experimental observations.

Table I gives a list of all parameters required for a standard calculation of defect evolution in a material under irradiation, and the possible sources for these parameters. Objects in this case are defects produced by the ion, electron or neutron irradiation. Events include all interactions between these defects and with the existing microstructure such as dislocations or grain boundaries. The starting point of the simulation is the distribution of defects produced by irradiation, including location (x, y, z coordinates) and type (vacancy, self-interstitial, impurity). In the case of continuous irradiation, defects are created following the rate of the experiment that is being simulated. As mentioned in the introduction, positions and type of defects can be obtained from classical molecular dynamics simulations with empirical potentials (CMD), from binary collision approximation (BCA) calculations, such as those obtained from SRIM [33] or Marlow [34], or as a random distribution of Frenkel-pairs, depending on the type of experiment to be modelled. For example, when damage is produced by electrons the latter approximation can be used. In the case of damage produced by light ions such as He, calculations using the binary collision approximation are appropriate. However, for self-irradiation and heavy-ions data from molecular dynamics simulations should be used. Often a combination of BCA and MD calculations is used to obtain the distribution of defects during irradiation for energies that cannot be reached by CMD alone. BCA is used to obtain the energies of recoils produced by the energetic particle along its path, but the final defect distribution produced is obtained from CMD simulations.

In some of the implementations of the OKMC algorithm, clusters are described by the location of its centre of mass, the number of defects and the type of defects in the cluster [15-22]. Codes such as Bigmac [35] or Lakimoca [19] use this approach. Each defect, either a single defect or a cluster, has associated a capture radius that depends on the number of defects of that object. This capture radius, *r*, is often defined as spherical:

$$r_n = \sqrt[3]{\frac{3n\Omega}{4\pi}} \qquad (4)$$

where *n* is the number of defects in the cluster and Ω is the atomic volume. This capture radius is used to define when two defects interact. Also when a defect dissolves from a cluster it is positioned outside this capture radius. When using this approach information regarding the lattice structure is lost. Strain effects such as the bias interaction between interstitials and dislocations can be included in the capture radius. It is also possible to include strain effects in OKMC using elasticity theory [36, 37].

In other implementations of the OKMC, the location of all the defects in a cluster are kept in the simulation. This is done in codes such as MMonCa [38] which has been used to model dopant diffusion in silicon [39] as well as metals [40-42]. This approach has the advantage that the capture volume is defined by the location of the defects in the cluster so complex geometries can be taken into account, beyond spherical volumes. . However, it is also computationally more expensive.

As mentioned above, in an OKMC simulation of radiation damage, the objects are defects produced during the irradiation, that is vacancies (V) and self-interstitials (I), but also impurities that could exist in the sample, such as carbon (C), or produced by transmutation in neutron irradiation or implanted, such as helium (He). Clusters that these defects can form among themselves must also be considered. In a system with 4 different types of objects (V, I, C and He, for example) the possible permutations between these different elements can give rise to a wide variety of complexes. The migration energy, dissociation of a defect from a cluster and the interaction between the different types of defects must be known for all these elements. For example the probability of a defect of type *t* undergoing a migration event is given by:

$$\Gamma_m^t = \Gamma_0^t \exp\left(-E_m^t / KT\right) \qquad (5)$$

where, as mentioned above, Γ^t_0 is the jump frequency, E^t_m is the migration energy for that particular type of defect, K is Boltzmann's constant and T is the temperature. When the object can migrate in any direction (three-dimensional migration) the jump is often performed by randomly placing the object within a sphere of radius the jump distance. When the migration of the object is restricted to one particular direction (one-dimensional migration), such as the case of some self-interstitial clusters in metals, a particular direction of motion with respect to the simulation volume is given to the object when it is created, and the jumps are performed only along that direction, for example, <111> for Fe or <110> for copper (Cu). .

Another basic type of event is the dissociation of a defect from a cluster. In this case, considering a diffusion-limited reaction, the probability of that defect dissociating from the cluster is given by:

$$\Gamma_d^t = \Gamma_0^t \exp\left(-\left(E_m^t + E_b^t\right) / KT\right) \qquad (6)$$

where E^t_b is the binding energy of the defect to the cluster. This energy depends on the number of defects in the cluster and the type of cluster.

Finally, all the possible interactions between defects must be taken into account. Here, the system can be made as simple or as complex as required by the particular objective of the simulation at hand. The simplest case could be considering only vacancies and self-interstitials and only one type of self-interstitial cluster. Then three reactions must be considered: $I_n + I_m \rightarrow I_{n+m}$ (self-interstitial cluster growth, where *n* and *m* are the number of defects on each cluster), $V_n + V_m \rightarrow V_{n+m}$ (vacancy cluster growth) and I_n+V_m which could result in three different outcomes: annihilation of defects if n=m, a self-interstitial cluster of size n-m, I_{n-m}, if n > m, or a vacancy cluster of size m-n, V_{m-n}, if m>n. Nowadays, however, calculations of defect evolution in metals are much more complex, including the presence of

impurities, such as C [41] or He [20, 43], different types of self-interstitial clusters [42] or even alloys [44]. Therefore, the list of possible reactions between defects can be very extensive. In such complex calculations one of the difficulties is to identify the relevant parameters that are the main drivers for microstructure evolution.

In the following sections we will describe some examples of OKMC calculations of microstructure evolution in irradiated metals under different conditions. These examples focus on the influence of the initial damage distribution, obtained from molecular dynamics simulations, on the microstructure that can be observed by techniques such as transmission electron microscopy.

3. Damage accumulation in pure metals: copper vs. iron

The first application of the OKMC method refers to damage evolution in two metals: Cu, with an f.c.c. structure, and Fe with a b.c.c. lattice, described in detail in reference [17] The influence of the initial damage distribution in microstructure evolution is clearly observed when comparing damage accumulation in these two metals. Molecular dynamics simulations of recoils with the same energy in these two materials show that, although the total number of defects produced is very similar, the defect distribution is different. Figure 2 shows a representative example for 30 keV cascades. Green spheres represent the location of vacant sites and red ones are self-interstitials. These cascades were calculated in this work using embedded atom type of potentials, [45] and [46] for copper and iron respectively. In copper almost every single cascade will produce a vacancy cluster at the initial location of the primary recoil surrounded by self-interstitial clusters, normally of smaller size than the vacancy one as shown in figure 2(a). These vacancy clusters evolve into stacking fault tetrahedra (SFT) over longer periods of time, as shown by other authors [47] and under certain conditions these SFTs can be formed directly in the cascades [48]. The size of these vacancy clusters is of the order of 1.5 nm in radius. In iron, the damage produced for the same recoil energy consists mostly of isolated vacancies, also located near the center of the collision cascade, surrounded by self-interstitial clusters, as shown in figure 2(b). Self-interstitial clusters are usually smaller in the case of Fe than in Cu.

Using a database of defect distribution from molecular dynamics simulations of collision cascades , Caturla et al. [17] modeled damage accumulation and microstructure evolution with OKMC. In this case 20 keV cascades were used. The calculations were performed for the same homologous temperature, 0.25 of the melting point (340 K and 363 K for Cu and Fe respectively) using the OKMC code BIGMAC, developed at LLNL [35].

The migration and binding energies for Cu vacancies were taken from calculations by Sabochick et al. [49, 50] while for self-interstitials the values of Schober and Zeller were used [51] obtained with empirical potentials. For iron values for vacancies and self-intersitials were calculated by Diaz de la Rubia and Soneda and used in these calculations [52]. Note that at the time, the state-of-the-art interatomic potentials for Fe predicted the <111> self-interstitial as the most stable configuration, with almost athermal migration (E_m ~ 0.1 eV) just like in the case of copper. Since then, DFT calculations have revealed that the most stable configuration for the self-interstitial in Fe is the <110> dumbbell with a higher migration barrier (Em ~ 0.3 eV [51]). Fu et. al [16] interpreted the experimental measurements of resistivity recovery of electron irradiated Fe through a combination of DFT and KMC, in this case EKMC. Simulations showed that a <110> dumbbell is the most stable configuration. Nevertheless, as an example of OKMC calculations and for the sake of comparison between

these two materials, particularly regarding the effect of initial defect distribution, the results first published in 2000 are still valid [17]. These results and the assumptions in the model are described briefly in the following paragraphs.

In the case of copper, self-interstitial clusters of sizes smaller than 60 defects were considered mobile. If they traveled a distance equivalent to 1 micron, they were removed from the simulation box, considering an effective grain size of 1 micron. In Fe, self-interstitial clusters were also considered mobile but when within the capture radius of each other they formed a junction and became immobile.

Damage accumulation at a dose rate of 10^{-4} dpa/s for both metals was calculated. In iron, 5 atomic parts per million (appm) of interstitial impurity atoms were included in the simulation, which act as perfect traps for self-interstitial atoms and small self-interstitial clusters.

Figure 3(a) shows the total cluster concentration as a function of irradiation dose for the two metals, copper (in red) and iron (in blue). Note that the total concentration is very similar for both metals. However, the cluster concentration measured experimentally with TEM is at least one order of magnitude lower in irradiated iron than in copper [54]. A more detailed analysis shows that in copper most self-interstitials and self-interstitial clusters disappear through recombination with vacancies or at grain boundaries, and most of the damage is formed by vacancy clusters. This is significantly different in the case of iron where both self-interstitial and vacancy clusters are present. However, the size of these clusters are very different between the two materials.Copper vacancy clusters with up to 30 defects are observed, as a consequence of the clustering occurring in the collision cascade, while in iron the largest vacancy clusters have less than 15 defects. Self-interstitial clusters in iron are larger with sizes with up to 60 defects in a cluster.

The comparison with TEM measured defect densities can only be done considering the threshold for visibility in these experiments. Using a threshold of 20 defects for vacancies in copper, equivalent to a stacking-fault tetrahedra of ~1.5 nm, 350 vacancies for a 1 nm void in Fe and 50 self-interstitials for a 1 nm loop in Fe, we obtained the results of the visible cluster concentration as a function of dose in copper and iron shown in figure 3 (b). Here, the one order of magnitude difference between copper and iron observed experimentally is clearly revealed.

The results for copper obtained from the OKMC model described here are well understood . The cluster concentration matched remarkably well the experimental measurements as shown in [17]. Besides the cluster concentration, the average number of vacancies in a cluster (~28) is also in agreement with the experimental results, (~2 nm). These simulations showed that SFTs in copper are formed directly in the collision cascade, which explains that the average size of defects is constant with dose. Therefore, for copper, the two most relevant parameters that explain the experimental observations are (1) formation of vacancy clusters within the few picoseconds time frame of the collision cascade (2) fast migration of self-interstitial clusters. For the case of iron, however, the correlation between simulations and experiments is not so straightforward. The lack of significant clustering within the collision cascade implies that most of the evolution of the clusters and growth to sizes that can be observed experimentally is going to occur through defect diffusion and defect coalescence. It also implies that impurities play an important role in defect accumulation and growth in Fe. The interaction between self-interstitials and vacancies with impurities can modify the density and size of defects accumulated in Fe. The description of these

interactions depends completely on the set of reactions that the user of the OKMC model has decided to consider as the important ones. That is, there is not an unambiguous description of defect evolution in Fe which is, in fact, the reason for much of the controversy in the modeling of microstructure evolution of this material. This discussion, however, is beyond the scope of this review paper.

4. Void swelling in f.c.c. and b.c.c. materials

The influence of initial damage structure on void swelling was also studied with an OKMC model [43, 55]. Void swelling is a phenomena observed mostly in austenitic steels while ferritic steels seem to be more resistant to it [56]. This effect is due to the stabilization of vacancy clusters by the presence of impurities, mostly helium, and the fast migration of self-interstitials to sinks [57]. In this case it is necessary to include in the OKMC model all the reactions between vacancies and self-interstitials with helium. The values for the binding energies of defects to clusters of type He_nV_m, where *n* is the number of helium atoms in the cluster and *m* is the number of vacant sites, must be obtained.. The usual procedure in this case is to compute the binding energies of a few representative but small clusters using DFT and then use an interatomic potential that has been validated with these results, to obtain the values for larger clusters. In the example presented here, the OKMC model [43, 55] included the values of biding energies of He_nV_m clusters calculated by Adams and Wolfer [58] using empirical potentials.In the calculations the binding energies were kept the same for all simulations and only the source term, that is, the initial distribution of defects, was changed. Defect distributions from iron and copper cascades, similar to the example in the previous section, were used.

Calculations were performed for the same total dose (0.1 dpa) and for different temperatures. For each cascade a Helium atom was introduced in the simulation, or a total of 1000 appm of He per dpa. The number of vacancies in clusters containing He were counted as those contributing to swelling. The equivalent of a percent of swelling was obtained from the vacancies in clusters with He and a relaxation volume of 0.8 of one atomic volume (Ω). This relaxation volume takes into account the migration of a self-interstitial to a sink and the change in volume in a void, as obtained from molecular dynamics. Figure 4 shows the results obtained for the percent of swelling as a function of temperature for the same total dose and for two different initial configurations of the cascade damage. We observed that when clusters are present in the collision cascade, a swelling dependence with temperature very similar to that measured experimentally for f.c.c. materials [56], with a clear swelling peak. Note that not only vacancy clustering is necessary to produce swelling. Vacancy clustering is needed as the seed to nucleate He_nV_m clusters, however, in order to have swelling an efficient removal of self-interstitials is required. In this case self-interstitials cluster during the collision cascade and can migrate to sinks such as dislocations or grain boundaries. These are, in fact, the main components of the ‘production bias’ model described by Woo and Sing [57] which is based on the early results of molecular dynamics simulations of collision cascades in metals.

In the case of cascade damage with small self-interstitial clusters and dispersed, isolated vacancies, calculations showed that swelling is very small (blue line in figure 4) in comparison with the case described above where defects were mainly clustered. This comparison was done for the same total dose measured in dpa (displacements per atom), that is, for the same number of defects produced in the irradiation. The green curve in this case includes not only the vacancies in He_nV_m but also those in vacancy clusters without He,

although no significant differences are observed. Swelling only increased slightly with temperature in this case, reproducing results observed in b.c.c. materials such as iron [54]. The reason for this difference was that in Fe vacancies must first migrate and form clusters that serve as the nuclei for He_nV_m bubbles or voids. Many of these vacancies recombined with the nearby self-interstitial clusters, which although may migrate, are smaller than in the case of copper, therefore more disperse increasing the probability of recombination with vacancies. Vacancies can also diffuse to other sinks such as grain boundaries or dislocations. In brief, higher recombination between vacancies and self-interstitials in a disperse collision cascade resulted in lower densities of nuclei for bubbles and voids and consequently lower swelling. As mentioned above, these results can only be qualitatively compared to experiments mainly due to the low doses reached in the calculations compared to existing measurements, as well as the lack of accurate enough parameters for He_nV_m clusters. Despite limitations, these simulations showed that some of the features observed in the microstructure evolution of irradiated materials are directly related to defect distributions produced in the core of a collision cascade. This link between the picosecond time frame of molecular dynamics simulations and experimental observations can be performed through the use of an OKMC model, including the three dimensional distribution of defects.

5. Influence of the interatomic potential on collision cascades and microstructure evolution: the case of Fe

The two cases described above involved a comparison between materials where the defect damage distribution originated in the collision cascade is quite different in terms of clustering of vacancies and self-interstitials. The influence of the interatomic potential on the collision cascade modeled by molecular dynamics and on the later evolution of the damage may be questioned. However, results obtained from molecular dynamics on defect distribution in the picosecond time frame cannot be directly validated experimentally. Only, as explained above, the evolution of this damage calculated with OKMC or rate theory models can be compared to experiments. However, many other factors are present in these simulations: migration energies, binding energies, reactions between defects or defect capture radius among others. Further, it is known that for the same material, recoil energy and temperature, different interatomic potentials will result in different clustering fractions of defects [59, 60], even though the total number of Frenkel pairs produced will be very similar. This raises the question of how these differences will affect the long term damage evolution. Are those differences significant enough to give rise to a difference on the long term evolution of the microstructure? In order to answer this question, Björkas et al [61]performed OKMC calculations where all parameters regarding migration energies, binding energies, defect interactions and capture radius were kept the same and only the database of collision cascades was changed, calculated for Fe with three different interatomic potentials and for the same energy (50 keV) and recoil conditions [61]. The following interatomic potentials were used for the cascades: the one developed by Ackland, Mendelev and Srolovitz (AMS) [62], the one from Dudarev and Derlet with short range potential fit by Björkas and Nordlund (DD-BN) [63] and one developed by Müller, Erhart, and Albe with short range part by Björkas and Nordlund (MEA-BN) [64]. All three potentials produced, on average, very similar number of Frenkel-pairs. However, the AMS potential gave rise to large self-interstitial clusters (more than 100 defects) that did not appear in the other two potentials within the statistics of these calculations (at least 10 cascades for each energy and potential). For more details see ref. [61]. Although the number of large self-interstitial clusters was small, it is interesting to see how the presence of these clusters affects the subsequent damage evolution.

Figure 5(a) shows the total number of clusters as a function of dose obtained for all three potentials and the same conditions of irradiation (dose rate, temperature, concentration of traps, etc.). No significant difference between the calculations was obtained in this case. However, when only visible clusters are considered, that is, clusters with more than 55 defects (~ 1 nm loop), then the difference in damage accumulation between the three potentials was clearly observed, as shown in figure 5(b). The potential with the largest self-interstitial clusters formed in the collision cascade (AMS) had a smaller slope for defect growth with dose but visible clusters appeared at a lower dose than in the case of the other two potentials with a steeper slope.

These results showed, firstly, the importance of the initial defect distribution on damage evolution. Even if the probability of having large self-interstitial clusters is small, their presence determines how the damage grows under subsequent cascades and over long periods of time. These results also provided a possible path for validating interatomic potentials in terms of cluster size distribution obtained in the collision cascade. Experimentally, the slopes that are measured for cluster concentration as a function of dose depend on the type of ion irradiation. In Fe, heavy ions give rise to a slope close to 1, since large self-interstitial clusters are formed in the collision cascade and easily grow to visible sizes.I Irradiation with Fe ions results in higher slopes, ~2, meaning self-interstitial clusters formed in the collision cascade are below the TEM visibility limit and coalescence between clusters as well as cluster growth due to diffusion of small self-interstitial clusters or mono-interstitials is required to reach visible sizes. Slopes as large as 4 have not been observed experimentally. This means that some type of clustering must occur within the collision cascade and that the MEA interatomic potential is not able to capture this behavior.

It is important to point out that the validation of the interatomic potential in this manner is neither straight forward nor complete. As mentioned earlier, many other parameters are involved when looking at microstructure evolution: migration energies, binding energies, interaction radius. The effect of these parameters was not studied in this work. Migration, binding energies and defect interactions are particularly important in the case of Fe where clustering in the collision cascade is generally small compared to other materials like W (see ref. [65]) or Cu (see figure 2(a)). Therefore, in Fe coalescence of self-interstitial clusters and growth beyond the collision cascade phase is needed to reach those sizes observed experimentally. And these processes are governed by reactions between loops and defects mobilities selected in the OKMC model. This approach could, in fact, be more successful in other materials where clustering in the collision cascade is larger, and the subsequent interaction among defects in the cascade does not play such as significant role as in Fe, like in the case of copper mentioned in section 3 above, or tungsten for b.c.c. materials.

6. Beyond the standard OKMC models

Currently there is a wide interest on enhancing the capabilities and accuracy of kinetic Monte Carlo models. There is a considerable effort devoted to improve the efficiency of this method so that longer times and larger system sizes can be modelled. A comparison between different codes and approaches can be found in references [29 & 30]. Nowadays, with the existence of supercomputers, parallelization would seem an obvious way to improve performance of these calculations. Parallelization is relatively simple in an EKMC or FPKMC algorithm. However, in the OKMC algorithm the total rate for all events in the system must be computed at each time step. This means that all nodes must know of all events at every time step. Recently, Martinez et al. [66] have developed a synchronous parallel algorithm which,

unlike previous attempts, solves the same master equation as the serial algorithm. In this case, the total rate of all events on each processor is kept fixed for all processors by including null events. A different approach has been developed by Jimenez and Ortiz [67] making use of GPUs for the parallelization of the OKMC algorithm.

Another aspect in the improvement of the OKMC method is trying to find a way to avoid the arbitrary selection of the events that go into the calculation. One of the great advancements in this area is what is known as on-the-fly kinetic Monte Carlo where the events are not pre-selected. The basic idea of this method is to compute the rates of the specific processes at the same time as the kinetic algorithm is evolving. That is, rates are not tabulated before the KMC calculation starts. This is particularly important for systems where the different type of events are very large and it is not possible, a priori, to know or define every scenario. This is, for example, the case of defect diffusion in alloys, in particular, in concentrated alloys, where the rate of a particular reaction will depend on the local environment. The methodologies used to implement an on-the-fly KMC algorithm differ between different groups and is adapted to the type of problem that needs to be solved. Probably the first on-the-fly KMC model is the one by Henkelman and Jónsson [68]. The authors use the dimer method [69] to obtain the saddle points between different states and construct an event catalogue. Stress-assisted diffusion of hydrogen in iron has been studied [70] combining on-the-fly calculations of barriers using empirical potentials and barriers pre-calculated by the more accurate density functional theory. . For other examples of on-the-fly KMC see references [71-74]. Xu et al [75] developed a promising on-the-fly method called self-evolving atomistic kinetic Monte Carlo (SEAKMC). In this case, longer simulation times can be achieved by defining “active volumes” around the defect of interest [76, 77]. Active volumes were also used in the work of Henkelman and Jónsson [68]. For further information about these methods see the article devoted to SEAKMC in this special issue. For the case of defect evolution in alloys other specific methods have been developed to produce the catalogue of transition rates in a more efficient way. One of those methods consists of using artificial neural networks to predict the values of the energy barriers [78]. Another method makes use of the phase diagram to bias defect diffusion and considers the local concentration to calculate the defect rates [79].

There are still challenges in the field of object kinetic Monte Carlo. Avoiding the *ad hoc* selection of the processes to include in the calculations still remains an open question. And probably one of the missing important components is taking into account in a general form the elastic field interactions between defects, although some important advances are being achieved as in the work of Mason et. al [80].

7. Conclusions

In this review, after introducing the methodology behind object kinetic Monte Carlo, we have shown how this algorithm can be used to study microstructure evolution of irradiated materials. The OKMC method provides a connection between atomistic simulations of migration energies, binding energies or defect distributions with experimentally meaningful time and length scales, preserving the three dimensional distribution of defects. Therefore, they provide a way of validating these parameters or evaluating their influence on microstructure evolution. In this respect, we have shown three examples of how the picosecond time defect distribution, obtained from molecular dynamics simulations of collision cascades, has an important impact on the microstructure evolution.

However, care must be taken when drawing conclusions from OKMC calculations as those described here. In all these simulations there is always a selection from the part of the user of the reactions and mechanisms included in the calculations. A model will only be robust if, with the same input parameters regarding defect migration, binding energies and interactions, is able to reproduce different experimental conditions. Further improvements of the OKMC algorithm to avoid this *ad hoc* selection of reactions are ongoing with the work of researchers at Oak Ridge National Laboratory in the US [75-77] or at Culham Center for Fusion Energy in Europe [80], among others. These models, however, are much more costly. If a connection to experiments at high doses (several dpa) has to be established, then it is necessary to make use of the OKMC approach described here with selected reactions. These advanced tools can help in the selection of the proper parameters and interactions.

Acknowledgments

I would like to thank my co-authors in the works briefly described here. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The research leading to these results is partly funded by the European Atomic Energy Community's (Euratom) H2020 WP 2016-2017 call NFRP13 (M4F) and in the framework of the EERA (European Energy Research Alliance) Joint Programme on Nuclear Materials.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time since this is a review article.

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Tables:

Table I: Description of required input parameters for a standard calculation of defect evolution in an irradiated material and possible methods and sources to obtain this input.

Input parameters required	**Possible sources/methods**
Initial defect distribution	CMD, BCA, random distribution
Capture radius	CMD, DFT, Elasticity theory
Migration energies	CMD, DFT
Dissociation energies	CMD, DFT, Elasticity theory
Defect-defect interactions	CMD, DFT, Elasticity theory

Figure captions:

Figure 1: Schematic representation of an object kinetic Monte Carlo algorithm.

Figure 2: Representative cascade damage produced by a single 30 keV recoil atom in (a) copper and (b) iron. Green spheres represent the location of the vacant sites while red ones are the location of self-interstitials.

Figure 3: (a) Total cluster concentration as a function of dose for copper and iron (b) visible cluster concentration.

Figure 4: Void swelling as calculated from the OKMC model as a function of temperature for two different initial damage distributions, one with clusters as in an f.c.c. material such as copper (red line) and one with mostly small clusters or isolated monovacancies and mono-interstitials, like in the case of iron (blue and green curves). In the green curve, both the vacancies in clusters containing He and those without are counted to obtained the void swelling. Total dose 0.1 dpa and 1000 appm He concentration.

Figure 5: Cluster concentration in irradiated iron as a function of dose for calculations with initial configurations of defects obtained with three different interatomic potentials (a) Total cluster concentration (b) Visible cluster concentration.

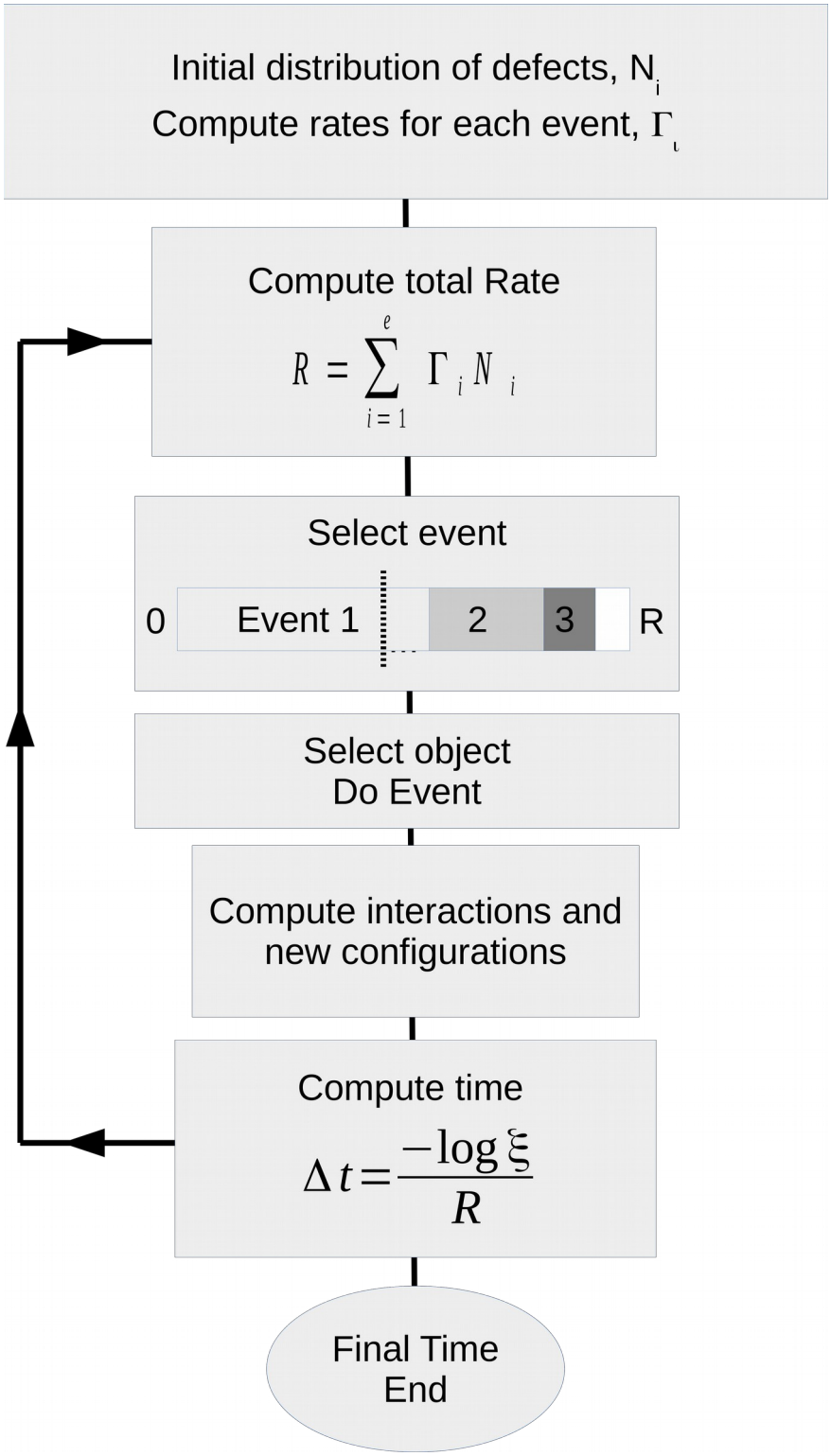
Initial distribution of defects, N_i
Compute rates for each event, Γ_i
Compute total Rate
$R = \sum_{i=1}^{e} \Gamma_i N_i$
Select event
0
Event 1
2
3
R
Select object
Do Event
Compute interactions and new configurations
Compute time
$\Delta t = \frac{-\log \xi}{R}$
Final Time
End

Figure 1

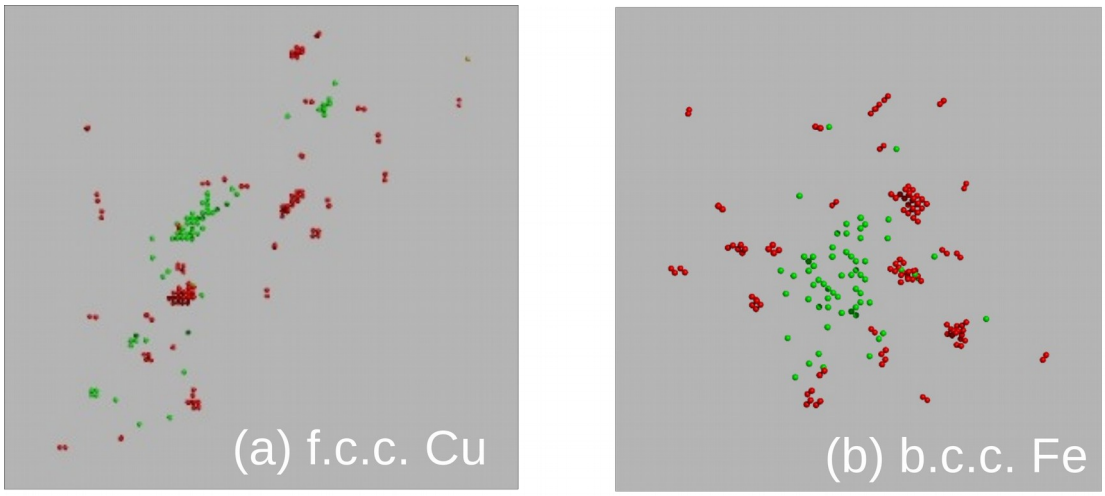

Figure 2

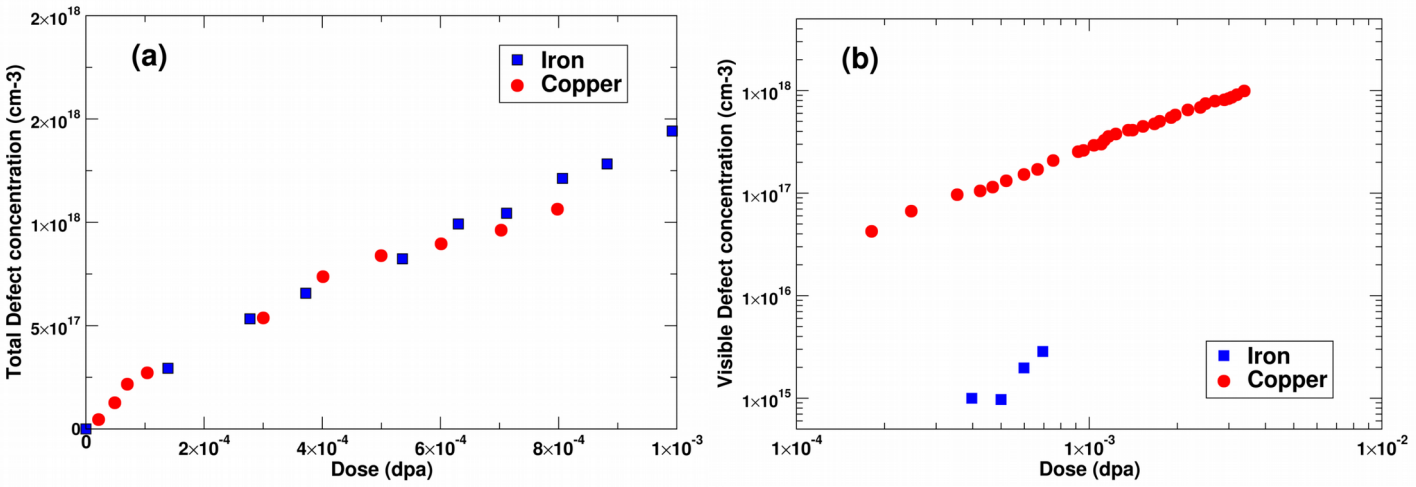
(a)
Iron
Copper
Total Defect concentration (cm-3)
2×10^18
2×10^18
1×10^18
5×10^17
0
0
2×10^-4
4×10^-4
6×10^-4
8×10^-4
1×10^-3
Dose (dpa)
(b)
Iron
Copper
Visible Defect concentration (cm-3)
1×10^18
1×10^17
1×10^16
1×10^15
1×10^-4
1×10^-3
1×10^-2
Dose (dpa)

Figure 3

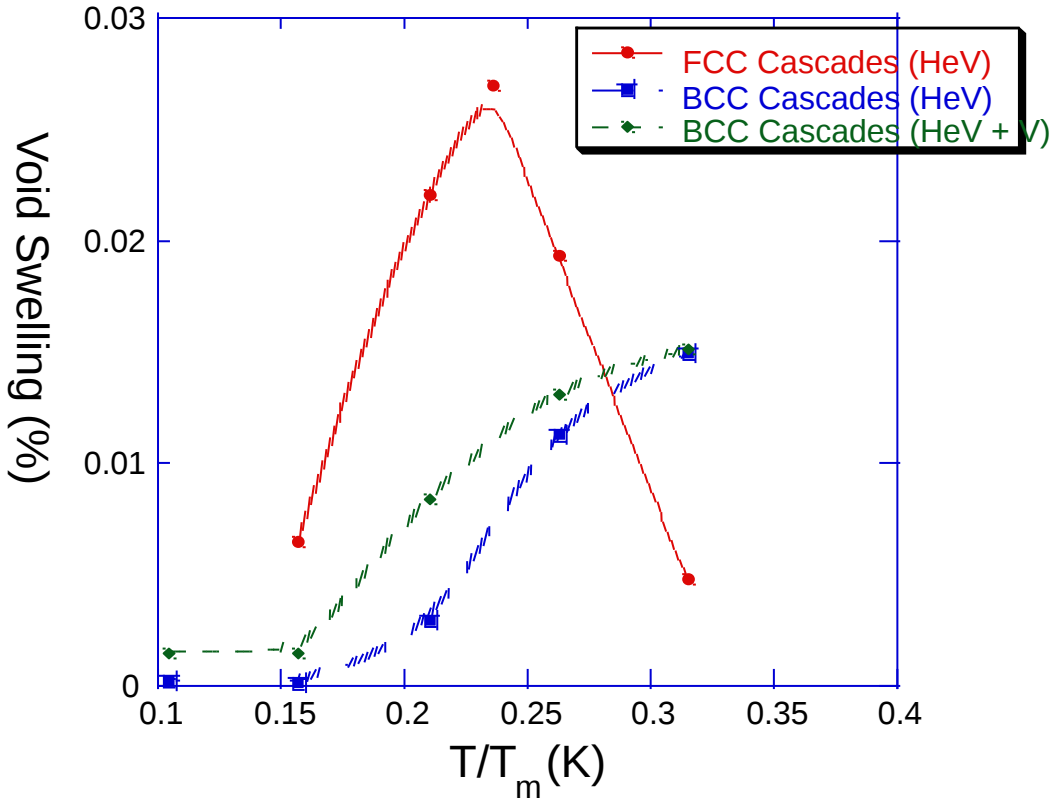
0.03
0.02
0.01
0
Void Swelling (%)
0.1
0.15
0.2
0.25
0.3
0.35
0.4
T/T_m (K)
FCC Cascades (HeV)
BCC Cascades (HeV)
BCC Cascades (HeV + V)

Figure 4

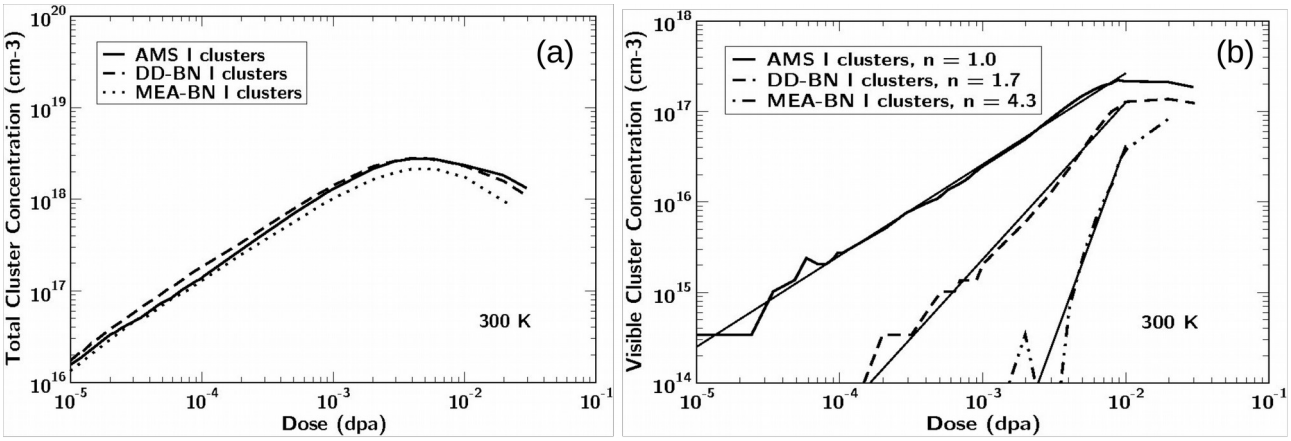
(a)
AMS I clusters
DD-BN I clusters
MEA-BN I clusters
300 K
Total Cluster Concentration (cm-3)
Dose (dpa)
(b)
AMS I clusters, n = 1.0
DD-BN I clusters, n = 1.7
MEA-BN I clusters, n = 4.3
300 K
Visible Cluster Concentration (cm-3)
Dose (dpa)

Figure 5