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Communication

Comments on the Mechanism of Detachment in Creep of Dispersion Strengthened Alloys at High Temperatures

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Abstract: This short article comments on the interactions between incoherent hard particles and dislocations, in dispersion-strengthened alloys, at elevated temperatures, which is the basis for their strength at high temperatures. We briefly review the details of the detachment model, discuss the limitations of the models and propose a new model for detachment. The purpose of this communication is to finally offer the creep research community a detailed mechanism for the dislocation detachment from hard particles, which has not yet been formulated.

Keywords: creep; dislocation detachment; particle strengthening

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In the past, there were two approaches to understand the atomic mechanism of dispersion strengthening: dislocation climb over the hard particles, where the activation energy would be that of lattice self-diffusion, and detachment from the particles. It appears that dislocations are attracted to hard particles at elevated temperatures, as theorized by Srolovitz et al. [1]. This theory appears to be well-accepted. Thus, at elevated temperatures, the rate-controlling process for plasticity is the thermally activated detachment of dislocations (that have climbed over the particle) from the matrix-particle interface. Nardone et al. [2] might be the first to suggest this, and the same is extensively and elegantly described by Artz and co-workers [3–8]. Others [9,10] have proposed relatively minor modifications to the detachment model of Artz and co-workers; however, these do not dramatically change the essence of the model. Experiments on the activation energy for the creep of these alloys reveal activation energy roughly a factor of four higher than the activation energy for self-diffusion [11,12]. Thus, the climb of the dislocations over hard particles as the rate-controlling process does not appear viable. Additionally, the stress exponents are much higher than observed for dislocation climb-controlled creep.

Basically, a dislocation that climbs over a hard particle needs to detach in order to continue to slip. It is now generally accepted that detachment is the rate-controlling process in the high-temperature creep of alloys with incoherent particles. However, a specific model for the detachment has never been presented. The detachment from the incoherent particle is presumed to be thermally activated. TEM (transmission electron microscope) observations are consistent with the model in that dislocations appear to be trapped at the matrix-particle interface [1]. TEM observations and the theory of Srolovitz et al. [1] are really the basis/justification for the detachment model. At first glance, it would seem that a higher elastic modulus that is typical of hard particles would repel the dislocations rather than trap them. However, at higher temperatures, the particle begins to act as a void, and the dislocation is attracted to the matrix-particle interface. This confirms that the activation energy of the detachment is fundamentally elusive.

Rosler and Artz [3] modeled the creep rate as a function of an interaction parameter, k, which is quantitatively unknown and cannot lead to an activation energy. Essentially, all models to date are based on a *single* detachment (detachment of a Burgers vector length

of dislocation) that presumably models the detachment of the entire dislocation from the particle. Therefore, the focus has been on the escape of a single dislocation segment on the order of the Burgers vector in length. Some have suggested that discontinuous dynamic recrystallization is the rate-controlling process; however, this has not gained acceptance [13].

The probability, p, that a small dislocation segment (one Burgers vector in length) can escape/detach from the interface would be described by:

$$p = v\, exp\left(\frac{-Q_d - Gb^3 + \tau b^3 + \int \frac{\tau b}{2r}}{kT}\right) \quad (1)$$

Back-stress is neglected in this equation as it appears negligible [14] in these sorts of dislocation structures. Here, Q_d is the activation energy for detachment from the incoherent interface, τ is the applied stress, G is the shear modulus, Gb^3 is the energy associated with the increase in dislocation line length, and τb^3 is the work done by the detaching dislocation segment. τb^3 term in the equation is the work to expand the loop to radius $b/2$, and ν is the vibrational frequency, which is often approximated by the Debye frequency (10^{13}–10^{14} Hz). The probability for detachment cannot be known as Q_d is unknown. This is a significant problem that is unlikely to be resolved soon. Computational atomic modeling might be necessary. In Equation (1), the second term is a result of the increase in elastic strain, as $Gb^2/2$ is the energy per unit length of dislocation. The last term in the equation is a result of the energy to separate the two screw segments shown in Figure 1.

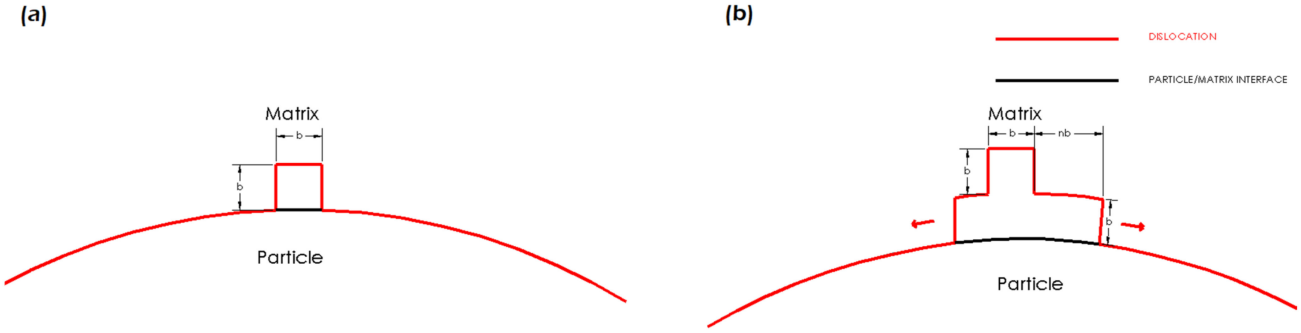

Figure 1. The initial detachment (**a**) leads to kink propagation (**b**) as part of the detachment process. The slip plane is the plane of the page, and the climb direction is perpendicular to the page.

A typical activation energy of 500 kJ/mol in particle strengthened alloys predicts a "p" value that suggests that the plastic flow is nearly athermal. We suggest that the escape includes the formation of a double kink, as illustrated in Figure 1a,b. The activation energy for double kink formation is roughly 100 kJ/mol in metals [15–17]. However, this energy does not include the energy associated with detachment of a Burgers vector length of a dislocation segment. Nevertheless, it, perhaps, provides a lower bound for the activation energy of a dislocation leaving the incoherent interface.

The second two terms in Equation (1) are the work done by the dislocation and the increase in elastic strain energy. Again, a fundamental explanation for the activation energy for dislocation detachment is currently speculative. The activation energy for detachment would vary with temperature, composition and structure of the incoherent interface and is probably difficult to model. Our calculation of the second and third energy terms in Equation (1) suggests relatively smaller values than the first term. This would lead to our calculation of double kink formation (in the absence of a detachment) to be less than reported for double kink formation in particle-strengthened alloys. Figure 1a is the presumed configuration for detachment in the Artz et al. [3] and other models, although it is not always explicitly stated. Figure 1b illustrates our proposal for the double kink formation and subsequent motion.

Historically, as mentioned earlier, the groups advocating detachment as the rate-controlling process are somewhat non-specific; the atomic details of the escape process are unclear. Again, it appears that all groups consider the rate-controlling process as represented by the detachment of a dislocation (Burgers vector in length) from the interface as in Figure 1a. Concepts beyond this idea are not provided. If, however, two or more adjacent Burgers vector length dislocations must escape together (at the same time), the activation energy is expected to increase beyond that for a single Burgers vector segment-length dislocation.

About ten years after proposing the detachment model, the Artz group suggested that the details of the detachment process involved jog formation in the interface dislocations [8]. It appears that most investigators are unfamiliar with this modification, or it is not endorsed by the research community. Though a conscientious effort, we did not find the proposition particularly useful for understanding the ejection of dislocations from the interface.

Here, we propose the escape of a Burgers vector length of dislocation leads to a double kink formation. We now believe that the rate-controlling process for complete detachment can involve the multiple and sequential (via the novel kink mechanism here) detachment of single Burgers vector length dislocations from the matrix-particle interface. The kinks, subsequently, can "unzip" the dislocation from the interface. The activation energy for this process is less by $Gb^2/2$ in Equation (1) since this involves the motion of a single kink.

One concern with the single ejection of a Burgers vector length of dislocation is that the radius of the ejected loop would have a radius of just b/2. It is unclear that the traditional equations for energy and attractive/repulsive forces would apply. In the case where the unattached portion of the dislocation meets at the interface, the motion would be similar to the kink model proposed; an unzipping would occur. Finally, we believe we have presented a detailed mechanism for dislocation detachment from a hard particle. We believe that we are the first to formulate a specific mechanism for detachment.

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