STATISTICAL MODELING OF LOAD-INDUCED FAILURE IN NANOPILLAR ARRAYS: FROM SINGLE-ELEMENT DISLOCATION DENSITY TO COLLECTIVE RESPONSE

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Based on a stochastic model for yielding in small specimens with a limited number of dislocations [1], we propose a Fibre Bundle Model approach [2] to simulate the compression of micro/nanopillar arrays. This work is motivated by the *smaller-is-stronger* phenomenon: the yield strength of micro/nanoscale specimens is significantly higher than that of their bulk counterparts [3]. However, nanoscale specimens – such as the Mo-alloy fibres produced by directional solidification of an Mo-NiAl eutectic with side lengths ranging from 360 to 550 nm – exhibit a large scatter in their yield strength. For these Mo-alloys, the strength values range from a high near the theoretical strength (approximately 9.2 GPa) down to the bulk strength (approximately 1 GPa) [4]. While such specimens were initially assumed to be nearly dislocation-free, transmission electron microscopy (TEM) observations of similar fibres [5] revealed that these as-grown specimens in fact contained a few pre-existing dislocations. Furthermore, the probability of encountering a strength-reducing dislocation is size-dependent: it is highly probable to find such a defect in a 30 μm long tensile specimen, whereas this probability becomes very low for a 1 μm long compression specimen.

In the present study, we assume that the system is composed of $N = L \times L$ almost identical pillars located at the nodes of square grid. Each pillar is characterised by its own strength threshold σ_{th}^{i} ($i = 1, 2, \ldots, N$), and the system is subjected to axial compression. These strength thresholds are dependent on the presence of pre-existing dislocations. Within our statistical model, we employ dimensionless units where the theoretical strength of a perfect, dislocation-free pillar is set to $\sigma_0 = 10$. In contrast, the strength of pillars containing dislocations is distributed within the range $(1,10]$, where the lower bound of $\sigma_b = 1$ corresponds to the bulk limit.

The number of pre-existing dislocations in each individual pillar is a random variable governed by a Poisson distribution with parameter λ. We have tuned this parameter from $\lambda = 10^{-5}$ up to $\lambda = 4$. At the lower limit, the array is nearly homogenous, consisting almost entirely of pillars with theoretical strength. As λ increases, the systems crosses over into an intermediate regime characterised by a mixture of two fractions: a significant number of ideal elements and a growing fraction of pillars containing strength-reducing dislocations. Finally, at high values of λ, the system transitions into a defect-dominated regime, where the mean system strength approaches the bulk limit and the scatter in σ_{th}^{i} is significantly reduced.

The framework utilizes a load-sharing scheme where the load from failed pillars is redistributed among the surviving ones. We investigate three different load-sharing protocols: global load sharing, local load sharing, and variable-range model, which acts as an interpolation between the two limiting cases.

References

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