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FIRST-ORDER SIZE EFFECTS IN THE MECHANICS OF MINIATURISED COMPONENTS

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ABSTRACT

Miniaturization is a general trend in the microsystems industry, driving the design and manufacturing of smaller and smaller devices, structures, and parts. When the part's dimensions are decreased to the same order of magnitude as the material's characteristic microstructural length scales, significant changes in mechanical properties may occur, i.e. a so-called ”size-effect”. Traditional continuum mechanics approaches thereby loose their validity and predictive nature. This work analyses size effects that are encountered first upon downscaling, including grain boundary effects, free surface effects, grain statistics effects. The separate influence of these first-order effects was carefully investigated using the following experimental and numerical methodology. To minimize second phase particle and strain gradient effects, tensile experiments were conducted on very pure aluminum sheet material, a relevant material in microelectronics applications. The deformation behavior under uniaxial tension was analysed by probing specimens with a limited number of through-thickness grains across the width, whereby the amount of grains is reduced towards a single grain in the cross-section. Local mechanical properties and microstructure, e.g. grain size and orientation, were analyzed using nano-indentation, X-ray diffraction analysis, orientation imaging microscopy, and optical surface profilometry. In addition, a 3D dislocation-field strain gradient plasticity model was employed to analyze the intrinsic size effects by numerical simulations, using a grain size and texture as obtained from the aluminum test specimens. Using a straightforward Taylor type analysis, the physical mechanisms underlying the different size effects were further clarified. It is well known that the flow stress of a structure can be increased by decreasing the structure's grain size, i.e. the Hall-Petch effect. However, this work shows that for miniaturized structures with a limited number of through-thickness grains a unique Hall-Petch relation does not exist, even though a grain boundary effect, i.e. increase in stress level (at a given strain) for decreasing grain boundary area per unit volume, is clearly present. When the microstructure (and thus also the grain size) is kept constant upon miniaturization, the free surface per unit area increases causing the stress level of the structure to decrease. This free surface effect becomes especially significant for less

than 15 grains in one of the components dimension. In addition, it is found that grain statistics effects also contribute to observed weakening, due to insufficient compensation of the local (weaker) material properties by the surrounding material (i.e. grains), i.e. these local zones will increasingly dominate the overall mechanical properties. Grain statistics also significantly increase the statistical variation in mechanical properties for these small-sized structures, an effect that is especially important for the reliability of miniature components. Finally, for structures with only a single grain in a cross-section, another size effect is observed; i.e. a small decrease in stress level is observed for decreasing cross-sectional area. The separate influence of these first-order effects as well as their interplay are explained in terms of the movement of the dislocations upon plastic flow.