ABSTRACT
Surface roughness effects result in asperity contacts spanning a wide range of length scales. In view of the multi-scale roughness of real surfaces, contact deformation of solid bodies exhibits strong scale dependence. Therefore, it is essential that contact mechanics analyses account for the evolution of deformation over a range of length scales, similar to that of the wavelengths comprising the topographies of the interacting surfaces. Results from finite element method (FEM) and molecular dynamics (MD) analyses based on continuum and discrete models of the interacting solids, respectively, reveal important effects of topography, length parameters (e.g., indenter tip radius, coating thickness, and penetration depth), surface traction, and elastic-plastic material properties on the deformation behavior at different length scales.

1. INTRODUCTION
Advances in microscopy techniques and computer technology have enabled contact mechanics studies of interacting solids possessing realistic surface topographies. The similar surface features observed at various magnifications have lead to the development of mathematical models for surfaces characterized by self-affinity property and scale invariant parameters, such as fractal geometry [1]. A fractal surface profile is characterized by scale-independent fractal parameters (i.e., fractal roughness $G$ and fractal dimension $D$) and can be approximated by a truncated series of cosine functions with wavelengths those of the surface topography [2]. Figure 1 shows a comparison of two fractal surfaces with different $D$ values. Although the surface with the higher $D$ value (Fig. 1b) is smoother, the contribution of higher frequencies is greater than that of lower frequencies, in contrast to the fractal surface with a lower $D$ value (Fig. 1a).

Fig. 1. Fractal surface topographies with (a) $D=2.3$ and (b) $D=2.6$ and identical all other surface parameters.

The previous example indicates that the contact deformation behavior is scale dependent. Therefore, multi-scale surface description accounting for self-affinity and constitutive laws valid at various scales are needed for accurate contact analysis.

2. RESULTS AND DISCUSSION
2.1. Multi-scale Continuum Contact Models
In general, contact of two solid bodies produces deformation both in the bulk and the contact interface. Although the macroscopic deformation behavior may be elastic, deformation at the asperity level may be elastic, elastic-plastic, or fully plastic, depending on the local interference and asperity radius of curvature. The size of the local contact region is controlled by the base wavelength of the contacting asperities and surface mechanical properties. Hence, the local deformation behavior changes significantly with the global interference (or normal load) and in the presence of a surface layer with elastic-plastic properties different from those of the substrate.

Figure 2 illustrates the importance of surface topography (scale effect) and layer stiffness (four times higher than that of the substrate) on the contact pressure (top) and subsurface von Mises equivalent stress (bottom) resulting from normal contact. Corresponding profile sections are also shown at the top. Remarkably different pressure peaks and stress distributions occur in each contact region. Notable stress discontinuities can be seen at the layer/substrate interface. Stress intensification adjacent to the contact regions and the layer interface indicates a greater probability for plastic deformation at the surface and bottom of the stiff layer.

Fig. 2. Contact pressure and von Mises equivalent stress for a layered medium indented by a fractal, rigid surface.
Figure 3 shows the first principal stress at the surface and below the surface resulting from sliding ($\mu = 0.5$) of a rough, rigid surface over the previous layered medium. The high tensile stress in the wake of asperity contacts and the layer interface reveals a higher possibility for surface cracking and/or delamination of the layer across the interface, depending on the local surface interference and sharpness of the asperities.

2.2. Molecular Dynamics Models

It is well known that continuum descriptions break down at very small surface interferences, e.g., less than about six times the lattice distance $a$. Therefore, contact deformation at the atomic level can be analyzed only with discrete-medium models and suitable dynamic methods, such as MD analysis.

Figure 4 shows the variation of the indentation load with dimensionless surface separation $Z/a$ for fcc substrate indented by a square pyramidal, rigid diamond tip. The repulsive force at the instant of contact ($Z/a \approx 0$) increases with the penetration distance at a rate controlled by the elastic response of the fcc medium. At a critical distance ($Z/a \approx -0.5$), an abrupt decrease in the normal force occurs due to the commencement of inelastic deformation, involving the displacement of some atoms from their atomic planes. The overlap of the unloading and loading paths during the retraction of the tip indicates an elastic response. Inelastic deformation does not occur during unloading. A force hysteresis is observed after full unloading. A constitutive relationship can be extracted from the force-distance response shown in Fig. 4, which can be used in multiscale contact simulations when the local interference is of the order of the lattice distance.

Figure 5 shows the variation of the shear (friction) force with dimensionless sliding distance. The steady-state friction response exhibits the periodicity of the fcc structure. Figure 6 shows the deformation in the fcc copper substrate due to indentation and sliding of prismatic and flat rigid diamond tips, respectively. It can be seen that indentation distorted loca atoms from the first and second atomic planes. MD results for repetitive indentation and sliding of diamond tips with various shapes and different material systems have been obtained in earlier studies [3,4].

3. CONCLUSIONS

FEM and MD simulation results illustrate a scale dependence of the contact deformation. Multi-scale surface topography description and constitutive contact models valid at various scales are essential in contact mechanics studies.

REFERENCES