

Polymer physics in nanoscale cutting: Opportunities for improved control in nano-manufacturing?

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Nano-scale manufacturing imposes demands on prediction of cutting processes on small scales. Specifically for applications that include optical functions, means to control the process parameter to produce high-quality and damage-free surfaces are of importance. Control through empirical testing may be time-consuming and costly. Predictive modelling schemes based on the underlying physical mechanisms could potentially be more generally applicable in manufacturing. The understanding of polymer physics and mechanics on sub-micrometre scale is emerging, and slowly but increasingly transferred from a fundamental research field to useful engineering applications. Nanoscale cutting of metals has been studied more and is better understood than that of polymers. For polymers, there are generally more complex interactions between deformation rates, temperature change and material transitions. These effects need to be included in physical models describing the cutting processes in polymers. Furthermore, the mechanical behaviour of polymers may be quite different on the nanoscale compared with macroscale. The material properties are frequently known to be size-dependent. This calls for development of experimental methods to characterize the material properties on the nanoscale, to be used in predictive modelling.

In this work, we have used an ultramicrotome, normally intended for preparation of ultrathin samples for transmission electron microscopy, instrumented with piezoelectric transducers to measure the cutting forces on sections down to about 50 nm thickness of thermoplastic PMMA. With this equipment, it was possible to investigate the effects of cutting speed and cutting thickness on the formation of surface damage in a well-controlled and reproducible manner. Using atomic force microscopy, the surface damage was identified as shear yield bands triggered by adiabatic heating. A suitable physical model including these observed phenomena made it possible to link the processing conditions with the onset of damage formation, i.e. the transition between a high-quality transparent surface and a damaged uneven surface. A finite element model was developed to predict the formation of the undesired shear bands. From an engineering perspective, such an approach could be potentially useful in improved manufacturing control. The present example supports the idea that material mechanics can be integrated in nanoscale manufacturing. In the future, it is not unlikely that instrumented nanomachining will provide on-line feedback through physical predictive models to adjust the processing parameters (forces, speed, etc.) to maintain a sufficiently high product quality at the highest production rate.