Measurement and simulation of temperature and strain fields in orthogonal metal cutting[1]

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Metal cutting is a highly coupled, nonlinear thermo-mechanical process in which friction and plasticity induced heating play a critical role. Much progress has been made in finite element based simulations of cutting. However, verification relies on comparing simulation results to global quantities such as cutting forces and chip morphology. Given the dynamic nature of metal cutting it would be useful to compare the evolution of local quantities such as strain and temperature fields to experimentally measured values. Accurate measurements of these would be valuable in building more reliable models of various cutting processes. In this work we present experimental investigations of the temperature and strain fields in a transient, orthogonal cutting experiment. Real time, high resolution temperature fields are acquired using a linear infrared (IR) array. Strain fields are measured using a $50\mu m$ grid on the workpiece, which is imaged after the test using an SEM. Simulations of the experiment are performed using ABAQUS. Computed global and local quantities are compared to the experimental results.

The experimental setup consists of a heavy pendulum with a cutting tool fixed to its end, falling under gravity from a height of $1m$. The cutting tool impacts a securely held workpiece of 1018 CR steel, cutting a $250\mu m$ chip at a speed of $3.2m/s$. The linear IR array maps temperature from a $500\mu m$ by $33\mu m$ region. The optical system is easily moved to view different regions of the cut. Position of the cutting tool is measured using a reflective photodiode system; this data is used to synchronize the temperature and cutting tool position and to determine the cutting speed. For example, Figure 1b compares the measured and computed peak temperatures as a function of height with respect to the cutting tool tip. Figure 1c compares the computed and measured temperatures as a function of time after the beginning of cutting at a fixed point in the workpiece. The computed temperatures tend to be somewhat higher than measured. This may be due to the limits on the spatial resolution of IR imaging. Very high temperatures may occur on length scales that are on the order of one wavelength of IR radiation.

To map strain fields, a square pattern of gold is deposited by coating through a mask. The deformed grid pattern on the chip surface is digitally imaged in an SEM and then analyzed to determine strain values. An example is given in Figure 2, which shows an image of the grid after an interrupted cutting test. In Figure 2c the shear strains just below the line of cut vary from 0.6 to 0 in a span of $200\mu m$ ahead of the tool. This is in quantitative agreement with the finite element simulations. Other micrographs, (Figure 3) show shear banding.

The methods developed in this research are independent of choice of material, depth of cut, tool type and cutting speeds. The simulations are sensitive to choices of material properties, fraction of plastic work converted to heat, and to coefficient of friction. As more is learned about these parameters, simulations can be made more reliable.

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Figure 1a) FEA simulation of metal cutting with temperature contours

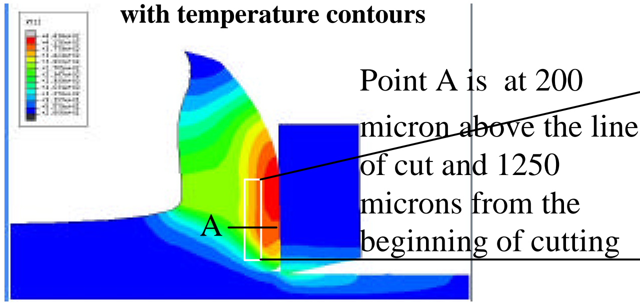


Figure 1b) Peak temperature as function of height with respect to the tool tip

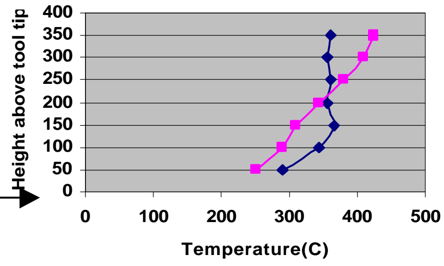


Figure 1c) Comparison of temperature rise measured experimentally and by FEA at point 'A'

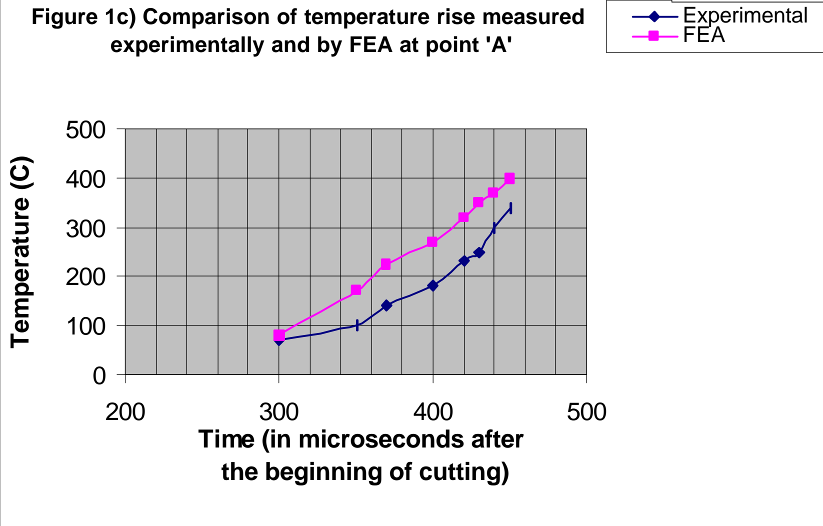


Figure 2a) Schematic representation of cutting process

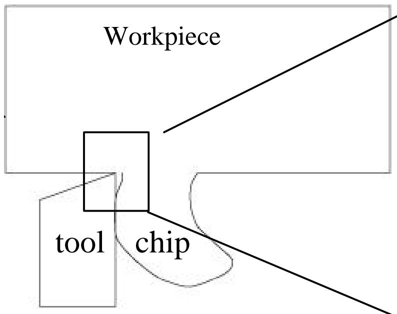


Figure 2b) SEM micrograph of interrupted cutting

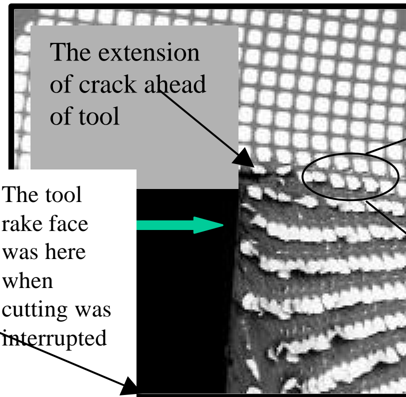
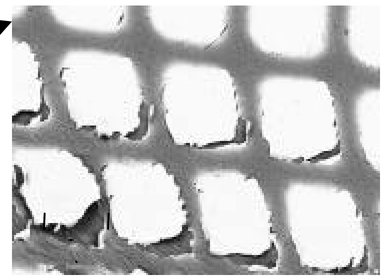


Figure 2c) SEM micrograph under higher magnification



50 microns

Figure 2d) Micrograph of removed chip