TEMPERATURE FIELDS IN ORTHOGONAL MACHINING

[1,2] Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, Indiana 46556

K.M. Vernaza-Peña[1], J.J. Mason[2] and M. Li[3]

[3] Alcoa Technical Center
100 Technical Drive
Alcoa Center, Pennsylvania 15069

ABSTRACT

During the machining of metals, plastic deformation leads to the production of heat in the material which results in themo mechanically coupled deformation in the cutting zone. In addition to significantly reducing production time, it is thought that high speed machining decreases the time for conduction of generated heat into the workpiece resulting in less distortion. It is important to characterize the thermal field in the cutting zone in order to completely understand such proposed advantages to high speed machining. In this work, HgCdTe infrared detectors are used to experimentally measure the temperature distribution at the surface of a workpiece during orthogonal cutting. A modified Hopkinson bar technique is employed to perform machining at speeds ranging between 15 to 45 m/s. Temperature fields are obtained in the orthogonal cutting of 6061-T6 aluminum alloy as a function of cutting speed, tool geometry and depth of cut.

MOTIVATION

Machining has been a topic of research for a long period of time due to its complex nature: it is a highly nonlinear and coupled thermomechanical process.

- Temperature is without a doubt the single most important factor in the machining process since it strongly affects tool life, chip morphology and power consumption.
- The heat generated during this process comes from two sources: the plastic work in the primary and secondary shear zones and friction at the tool-chip interface.
- In the primary shear zone, local heating due to plastic work can cause temperatures to become very high, thus softening the material and allowing for greater deformation and further heating sometimes leading to shear band formation.
- Since it is a short event, there is less time for the generated heat to be conducted to the workpiece so there is less distortion.
- Cutting process at high speed can lead to shear localization which will result in the production of serrated chips producing high tool wear.
- The precise and accurate measurement of temperature fields during metals manufacturing and processing is of great interest since the final physical properties of the finished products depend strongly on the process temperature.

High Speed Machining Advantages

- High production rates
- Low residual stresses
- Less deformation of workpiece
- Better surface finish

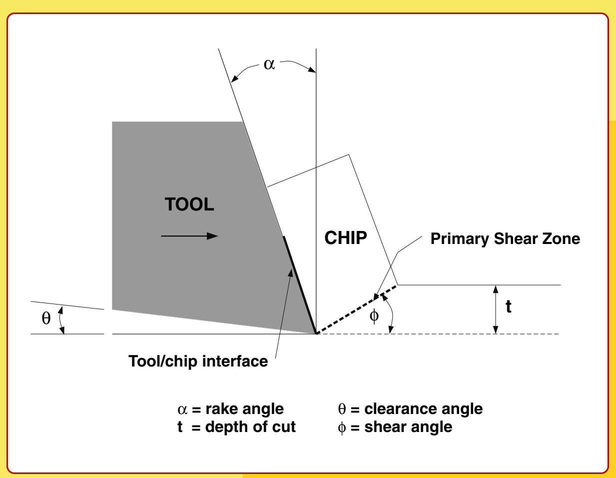


Figure 1: 2D Orthogonal Machining Model

EXPERIMENTAL SETUP

The experimental setup is composed by two parts:
- an orthogonal machining loading device obtained using a Hopkinson bar
- a high speed temperature recording system which consists of a linear array of HgCdTe photovoltaic photon detectors.

ORTHOGONAL MACHINING HOPKINSON BAR APPARATUS

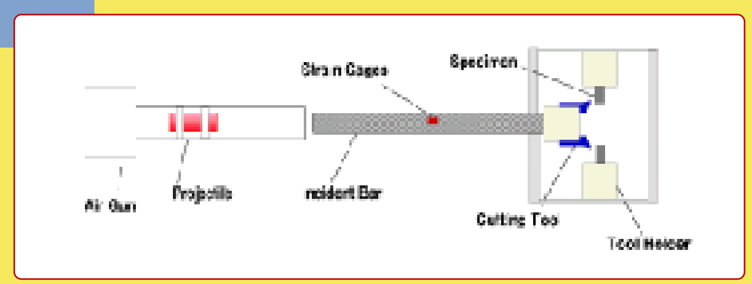


Figure 2: Schematic drawing of the orthogonal machining Hopkinson bar apparatus.

- One end of the elastic bar is aligned with the barrel of the air gun to ensure normal impact by the projectile while the other end, which has the cutting tools attached to it, is aligned to the workpieces to again have a normal impact.
- The cutting tools are bolted to the tool holder, which in turn is held in position on the elastic incident bar by means of setscrews.
- The maximum allowable velocity of the tool is equal to the maximum allowable impact velocity of the projectile which is 120 m/s.

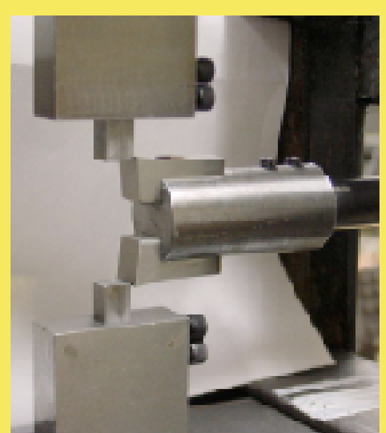


Figure 3: Cutting tools and specimens

MEASURING THE TEMPERATURE FIELD

- A linear array of 16 photoconductive Mercury-Cadmium-Tellerium (HgCdTe) detectors used in these experiments.
- Each detector is 80 mm x 80 mm with a center-to-center spacing of 100 mm and a total length covered of 1.58 mm.
- The array is mounted behind a sapphire window in a liquid nitrogen Dewar to cool the detectors to 77 K in order to minimize their electrical noise and maximize their sensitivity.

- In order to measure the temperature distribution, the sixteen elements of the detector array are focused on the surface of the workpiece on a line perpendicular to the cutting path.
- A Newtonian optical system, consisting of a concave mirror and two flat mirrors, forms the basis of the optical system used to do so.

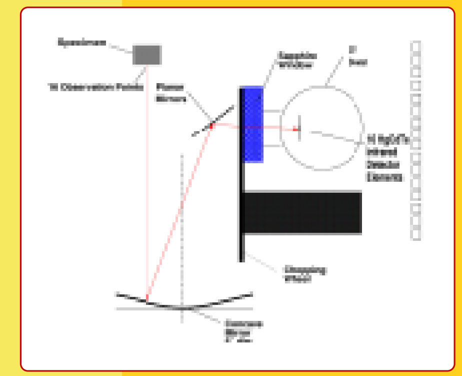
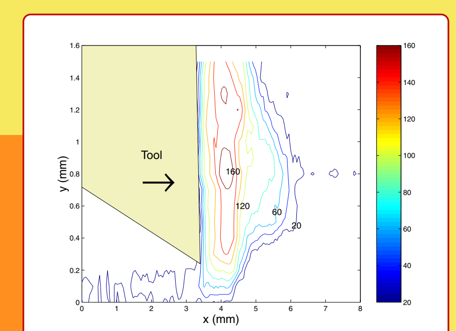


Figure 4: Schematic of Newtonian optical system

- An experimental calibration that provides a direct relationship between the temperature on the surface of the specimen and the output voltage of the infrared detectors was performed.
- An experimental temperature field distribution is derived by converting the time axis into distance parallel to the cutting path, using the measured cutting speed.

TEMPERATURE FIELDS



An experimental temperature field distribution is shown for 6061-T6 aluminum alloy where the depth of cut was 0.5 mm, the velocity of the cutting tool was 15.0 m/s, the rake angle was 5 degrees and the clearance angle 8 degrees (temperature in the tool is not imaged). The maximum temperature obtained on this test was 181 degrees Celsius. The y-axis is the position of the detectors. A small primary zone can be seen extending ahead of the crack tip. In addition, it can be seen that the heating zone extends below the tool. Note that the thermal trail observed below the tool tip indicates that adiabatic conditions do not apply at the cutting speeds employed on this series of experiments

Figure 5: Temperature field for aluminum 6061-T6, 5° rake angle, 0.5 mm cut and 15.0 m/s. A maximum temperature of 180°C is recorded.

The effect of depth of cut on the temperature field was studied for a cutting velocity of 15 m/s, 5° rake angle and 8° clearance angle. The results are presented on Table 1. It is observed that the maximum temperatures increase with increasing depth of cut as expected.

Depth of cut (mm)	Maximum temperature (°C)
0.5	181
1.0	207
1.5	238

Table 1 — Maximum temperatures at cutting speed of 15 m/s and rake angle of 5°

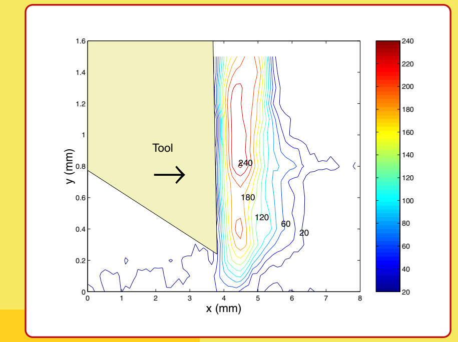


Figure 6: Temperature field for aluminum 6061-T6, 5° rake angle, 0.48 mm cut and 30.1 m/s. A maximum temperature of 251°C is recorded.

As the temperature fields are examined, a distinctive primary shear zone is observed, being the isotherms the evidence of its presence. This heating along the shear plane contributes to the deformation, i.e. the formation of the chip. As the rake angle increases from 5 to 15 degrees, the temperature becomes localized near the tool face. The higher rake angle creates a longer heated contact zone along the length of the rake face of the tool and decreases the plastic zone ahead of the tool. The friction work appears to have increased while the plastic work at the primary shear zone seems to have decreased.

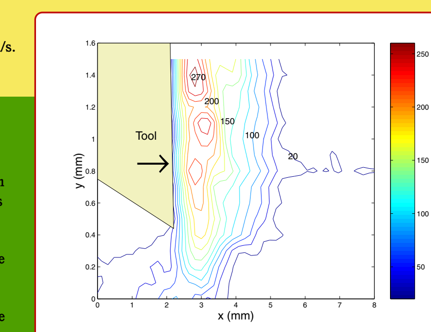
The effect of cutting velocity on the temperature fields is studied. The next two Figures, present the results for cutting 6061-T6 alumimun alloy at 30 m/s and 45 m/s with 0.5 mm dept of cut, 5° rake angle and 8° clearance angle. It is seen that for the velocity range studied here, the mean shear zone temperature increases with increasing cutting speed.

The effect of rake angle was studied as well. Table 2 present the maximum temperatures for rake angles of 5, 10 and 15 degrees at two cutting velocities: 30 m/s and 45 m/s for a constant depth of cut of 0.5 mm. It is observed that the maximum temperatures decrease with increasing rake angle as expected. This is because lower work is required for higher rake angle cutting.

Rake Angle (°) (°C)	Maximum temperature at cutting speed of 30 m/s	Maximum temperature at cutting speed of 45 m/s (°C)
5	251	290
10	237	248
15	196	200

Table 2 — Maximum temperature as a function of rake angle with a constant depth of 0.5 mm

Figure 7: Temperature field for aluminum 6061-T6, 5° rake angle, 0.5 mm cut and 45.5 m/s. A maximum temperature of 290°C is recorded.



CONCLUSIONS

The velocity effect study showed that maximum temperature increases as the velocity increases for low rake angles. At high rake angles, the mean shear-zone temperature tends to become constant, as seen for a 15° rake angle. The rake angle effect study presented here shows that the maximum temperature is higher for lower rake angles and that the maximum temperature shows an obvious trend to decrease as the tool rake angle increases. In addition, for the aluminum alloy studied here, 6061-T6, evidence of a primary shear zone is not as noticeable at higher rake angles. At higher rake angles, plastic shear strain decreases. A high temperature zone appears along the length of the cutting tool rake face indicating dominance of the friction component of heating.

The experimental technique developed can be employed to test a broad range of cutting parameters; a large range of speeds can be investigated, from conventional machining of aluminum alloys to very high speed machining.

REFERENCES

1. Boothroyd, G., and Knight, W.A., 1989, *Fundamentals of Machining and Machine Tools,* Second ed., Marcel Dekker, Inc., New York.
2. Shaw, M.C., 1984, *Metal Cutting Principles,* Clarendon Press, Oxford.
3. Trent, E.M., and P.K. Wright, 2000, *Metal Cutting,* Butterworth Heinemann, Woburn, MA.
4. Vernaza-Peña, K.M., Mason, J.J., and Li, M., 2001, "Experimental study of the temperature field generated during orthogonal machining of an aluminum alloy," to appear in Experimental Mechanics.
5. Vernaza-Peña, K.M., Mason, J.J., and Li, M., 2002, "Temperature fields in aluminum during orthogonal machining under different rake angles and cutting velocities," submitted to ASME Journal of Manufacturing Science and Engineering.