Georgia Institute of Technology

Manufacturing Research Center

MiTi-MARC STTR Project
ULTRA-HIGH-SPEED MICRO-MILLING MACHINE
GT Project Number 12966G1 (Doc id: 103789)
Final Monthly Report #9
Covering September – December of 2007

High Speed Spindle Testing with GT Micromachining Center: Round One – September Tests
The high speed spindle was shipped to Georgia Tech in early September and preparations were made for initial integration with the micromachining center at Georgia Tech. On September 12th, MiTi engineers arrived and the afternoon was spent installing and test the spindle and setting up all of the data acquisition equipment. The integration went as expected although it was necessary to machine the high-speed spindle mount on the following day in order to make a good fit with the existing micromachining center frame. As was the case during initial testing of the spindle at MiTi, compressed bottled air was used to power the spindle. A HP FFT spectrum analyzer was used to monitor spindle speed through sensors mounted in the high-speed spindle assembly.

The goal was to perform grinding of 6061-T6 Aluminum and testing began on September 13th once the spindle was successfully mounted to the machine frame. In order to establish initial contact with the workpiece, the spindle speed was set to ~ 300,000 rpm and several runs were carried out in which the tool traversed the complete length of the part in the x direction (see Diagram 1 below) and at the end of travel in the x direction, the workpiece was stepped over by 50μm in the y-direction (closer to the tool). The next run was performed such that the tool now traversed the length of the part in the opposite x direction. This process was repeated several times while monitoring the cutting forces on the computer readout, and after each pass, the workpiece was checked for evidence of any machining that took place. Several runs were carried out in this fashion and it did not seem as if the tool was making contact. On the last run performed, the tool did make contact with the workpiece, and after ~ 3.4 mm of grinding, the tool broke.

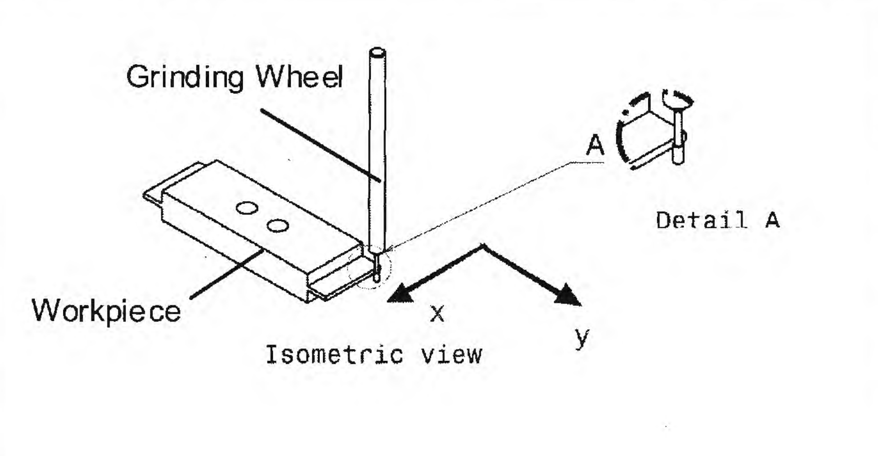


Diagram 1 – Diagram of grinding wheel in contact with workpiece.

Upon inspection of the workpiece under the microscope (see Figure 1 below), it was easy to see that the surface finish of the machined area was very rough and it appeared as though the material had flowed during grinding and perhaps had loaded up the wheel, causing the tool to break. As a result, it was decided that in the next round of testing, a steel work piece would be used.

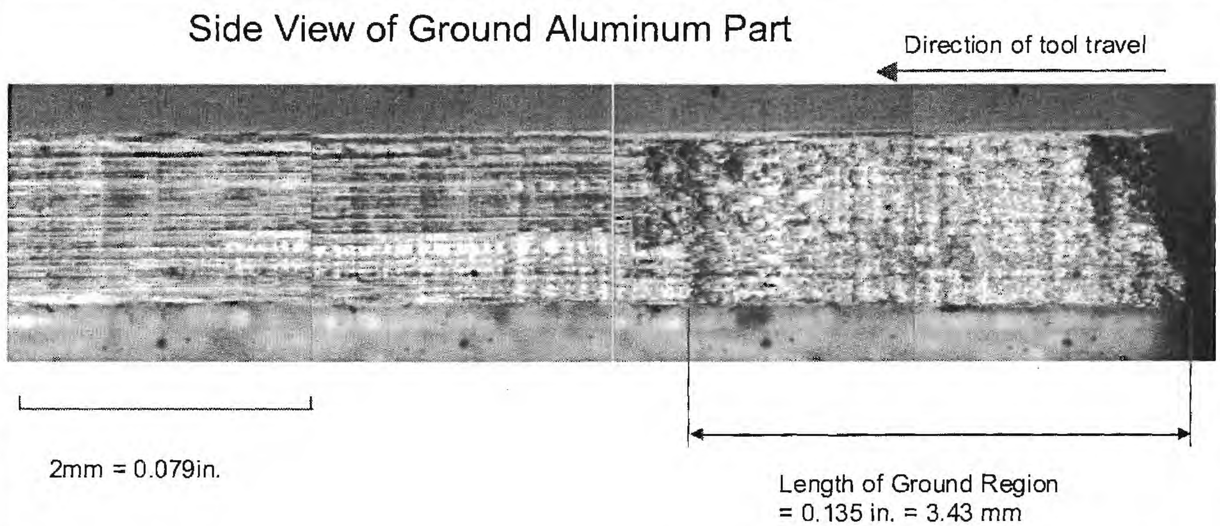


Figure 1 – Side view of Aluminum workpiece that was ground. Ground region is identified above.

High Speed Spindle Testing with GT Micromachining Center: Round Two – October Tests
The high speed spindle was shipped to Georgia Tech once again in early October and machining trials were performed with the high speed spindle on October 23^{rd} and 24th. Grinding of steel was performed using a 0.030" diameter (762µm), 240 grit CBN abrasive, electro-plate bonding Di-coat grinding wheel. Ultra-Machinable 12L14 Carbon Steel was chosen as the workpiece material in an effort to avoid loading of the grinding wheel which occurred in the September tests when grinding Aluminum.

Once the spindle had been installed on the machine, several test passes were taken in order to establish initial contact of the tool on the workpiece. The spindle speed was set to ~ 300,000rpm (reading on the FFT was ~ 4.99kHz) and the workpiece was moved to a location such that tool was centered on the workpiece in the x direction (see Diagram 1 above). Holding the x location constant, the workpiece was fed into the tool in the y direction in increments of 20µm at a feed rate of 5mm/min. Several repetitions (~7-10) were performed using this procedure and the workpiece was checked for any evidence of tool/workpiece contact after each repetition. No evidence of contact was found, so the procedure was repeated with 50µm increments. On the third or fourth repetition, a popping noise was heard and after inspection, it was found that the tool did make contact with the workpiece and the tool had broken (hence the noise that was heard).

Evidence of this cut can be seen in Figure 2 below which shows a top view and side view of the machined surface. This cut is identified as "First Contact Day 1". It is interesting to note that the gouge created in the part is much deeper than 50µm even though this is the increment that was used for slowly moving the workpiece into the tool. One other notable observation is that the width of the gouge is approximately 1.78mm (or ~ 2.3X the diameter of the tool). One possible explanation for these phenomena could be wobble/runout created in the tool/spindle after initial contact was made between the tool and workpiece.

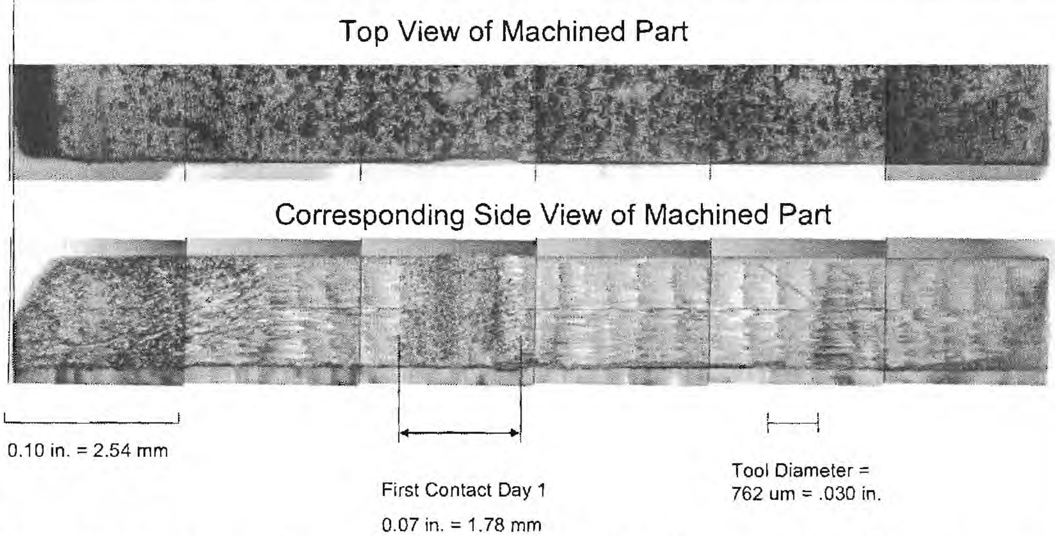


Figure 2 – Top view and corresponding side view of machined part from October tests.

The rotor was replaced and a fresh tool was added. Rather than trying to establish initial contact between the tool and the workpiece by moving the workpiece only in the y direction, several runs were carried out in which the tool traversed the complete length of the part in the x direction and at the end of the travel in the x direction, the workpiece was stepped over by 50μm in the y-direction (closer to the tool). The next run was performed such that the tool now traversed the length of the part in the opposite x direction. This process was repeated several times while monitoring the cutting forces on the computer readout, and after each pass, the workpiece was checked for evidence of any machining that took place. After the 6th run, the workpiece was checked and there was no evidence of machining on the workpiece (apart from the original gouge, discussed above, that had been made in the center of the workpiece).

As the 7th run was taking place, it did not appear to the naked eye that there was tool/workpiece contact and after ~ 3 mm of total positioning stage travel (corresponding to ~ 2.5mm of travel on the part -- since the tool was started in a location clear of the part), the feed was stopped, and approx. 20 seconds later, the air to the spindle was slowly shut off. As the air to the spindle was slowly being cut-off, a popping noise was heard and the tool broke. By examining the workpiece, it could be seen that there was evidence of machining along the first 2.5-3 mm of length on the left hand side of the part as shown in Figure 2, in the region just above the picture scale bar. The cutting conditions used in the 7th run and the 6 preceding it were the following:

Spindle Speed: 299,520 rpm (4.992 kHz on FFT)
Feed: 2 mm/min
Stepover in y direction with each pass (DOC): 50μm

Once again, it can be seen that the surface finish in the ground region of the part is very rough and it seems that material flow occurred in the steel workpiece. Perhaps there was also loading of the tool.

After this run, the tool was replaced and another run was performed at a much higher feed rate and spindle speed. The cutting conditions were the following:

Spindle Speed: 450,000 rpm (7.5kHz on FFT)
Feed: 1mm/sec
DOC: 50μm

After ~ 1 second of cutting, the tool broke. It is believed that the evidence of this cut can be seen in the first ~1mm on the left side of the part shown in Figure 2. The cutting conditions used for this cut were very aggressive and provide a likely explanation for why the tool broke so quickly.

Cutting force data was taken using the Kistler MiniDyn for all of the runs discussed above and the data files, along with the MATLAB program used to create charts of the data were provided to MiTi to perform data analysis, per their request. As a result, force data results will be provided by MiTi engineers and are not included in this report.

Laser-based Tool Edge and Workpiece Edge Detection:

As reported in the March 2007 project update report, it was demonstrated that the centerline and the vertical tip of the tool could be located using the He-Ne laser at Georgia Tech. Acoustic emission was also shown to be useful for identifying when the tool was in contact with the workpiece. However, these techniques alone provided no means of predicting the XYZ position of the positioning table at which the tool edge makes contact with the workpiece surface. In other words, it was possible to locate the tool tip and edges and it was possible, through use of acoustic emission to determine if contact was being made with the workpiece, however, it was not possible to predict the exact location in space where initial contact was made. Through testing with the high speed spindle, it was determined that it is more critical to know the exact location of contact between the tool and the workpiece when using the high speed spindle than it was when using the low speed spindle, in order to avoid breaking the tool. In light of this necessity, a method has been developed which provides the location of the intersection between the workpiece edge and the edge of the tool in terms of the XYZ position of the positioning stage.

As shown in Figure 3 below, the tool is fixed and the laser emitter is moved along parallel guides in the x direction while watching the graph of detected laser power on the computer monitor. As described in the March 2007 monthly report, the minimum point on this graph (see Figure 4) corresponds to the location of the center of the tool (in the x direction). Once the center of the tool is found, the laser emitter and detector are fixed at this location. The workpiece is then moved, via movement of the XYZ positioning stage, in the x direction as shown by the arrow in Figure 3. Watching the detected laser power graph on the computer monitor, the x-coordinate of the positioning stage at which the workpiece begins to block the emitted laser beam can be identified (from the positioning stage readout) and recorded. This x-coordinate provides the location of the intersection of the edge of the workpiece and the center of the tool (as illustrated in Figure 5 (a)). However, in order to get the value of the x-coordinate of the positioning stage where the edge of the tool makes contact with the edge of the workpiece, we subtract half the diameter of the tool. This new x-coordinate marks the x intersection of the edge of the workpiece and the edge of the tool as shown in Figure 5 (b). Of course, the z location of workpiece/tool contact can be identified with the naked eye, and the y location of contact, as shown in Figure 3, does not need to be known before cutting begins (this is direction that the tool is fed along the edge of the workpiece).

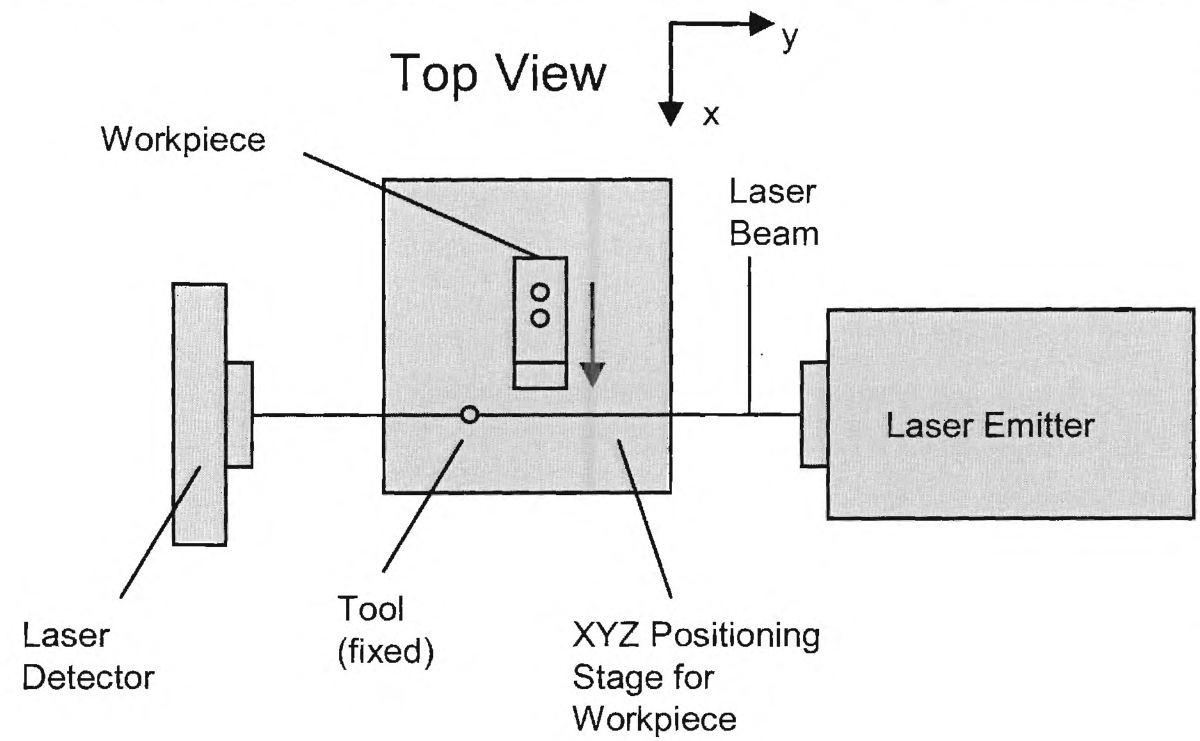


Figure 3 - Diagram of method used for determining the location of the intersection of the workpiece edge and the tool edge.

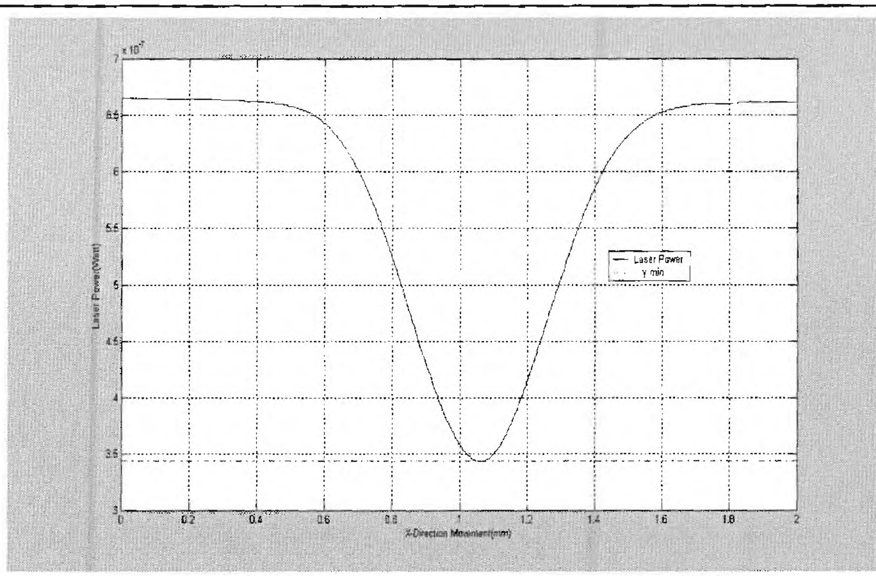


Figure 4 – Example graph of detected laser power versus laser beam position with respect to the tool. The lowest point on the graph represents maximum blockage of the emitted laser beam and the location of the center of the tool.

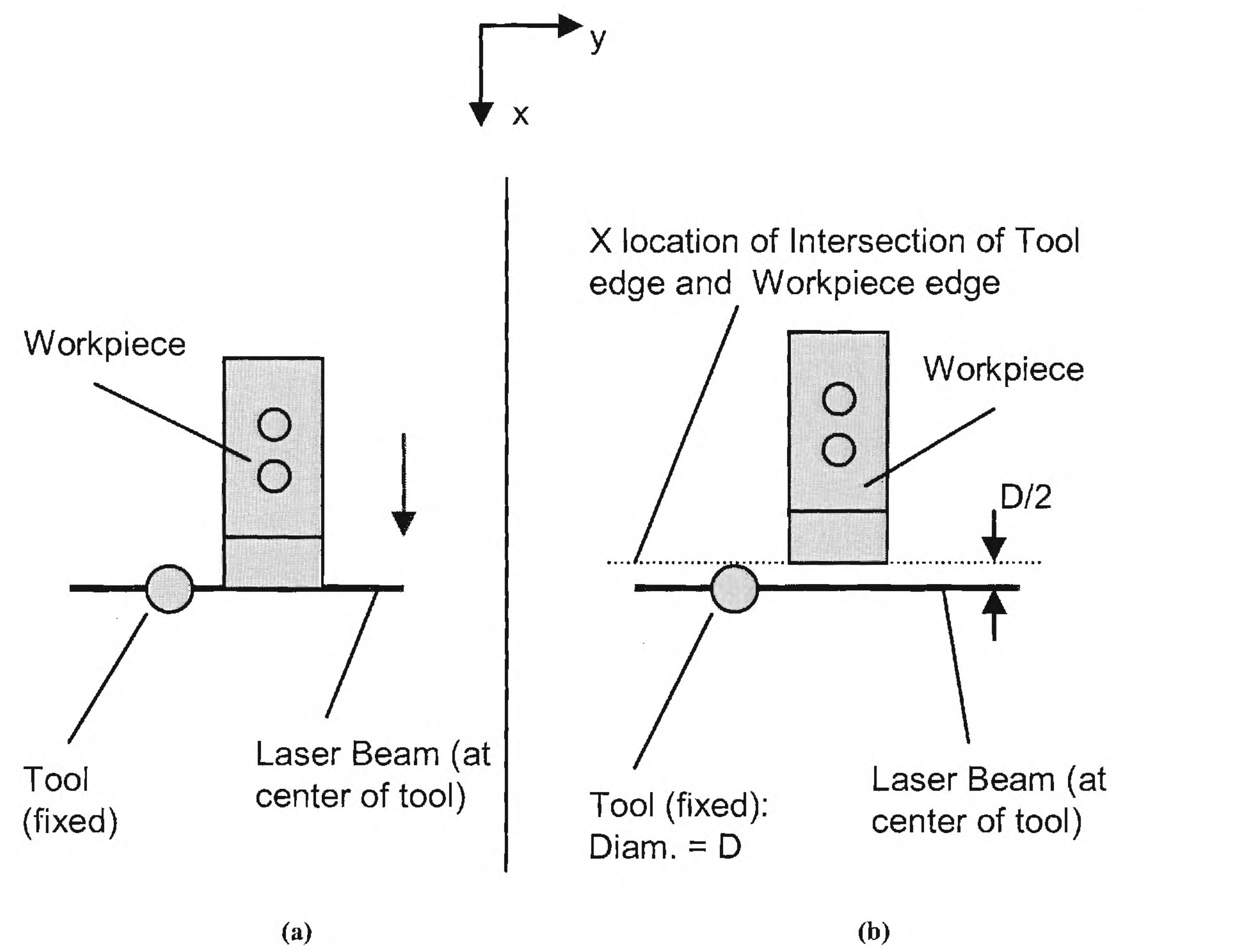


Figure 5 – (a) Workpiece edge making initial contact with laser beam, and therefore x location of center of tool; (b) workpiece edge lined up with x location of edge of tool.

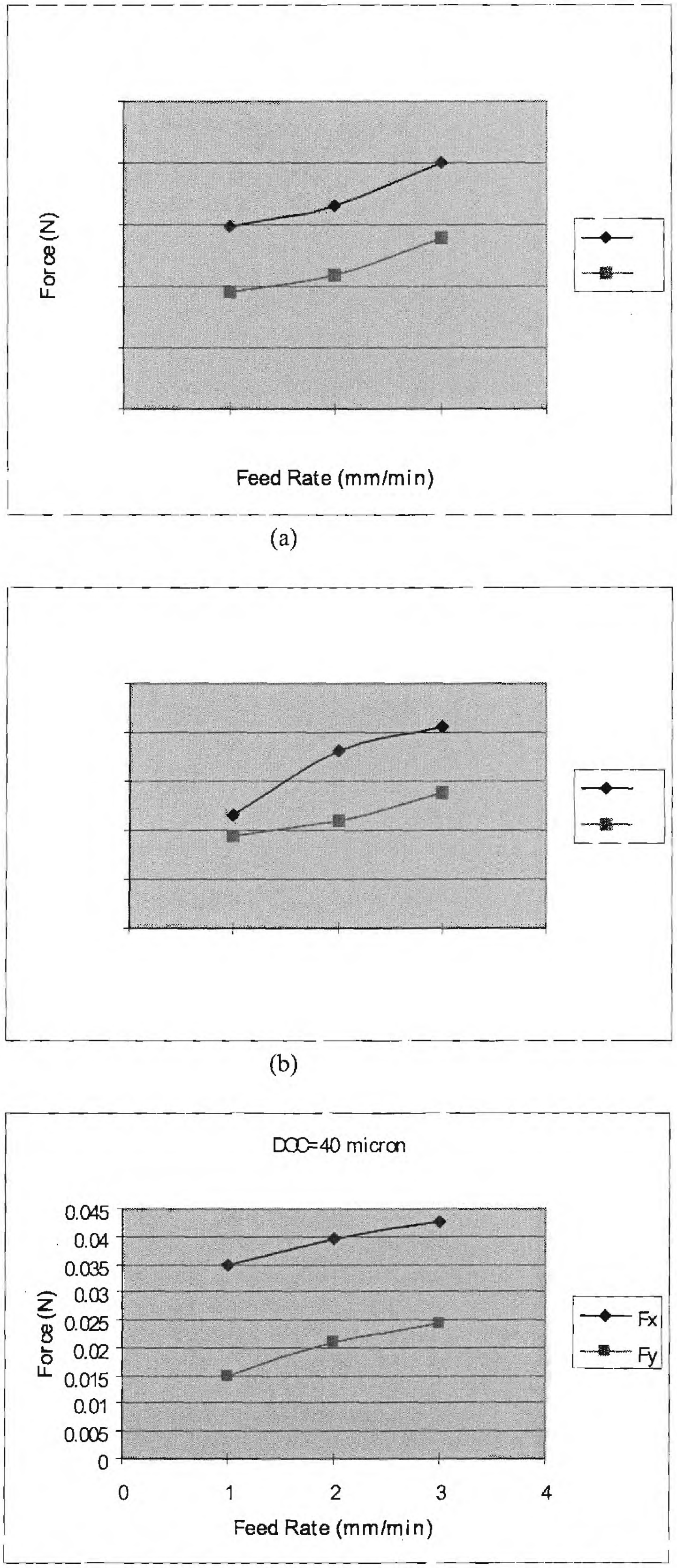
Proof of concept for the above described method for detecting the location of the edge of the workpiece and the edge of the tool have been demonstrated at Georgia Tech. Further testing and refining of the method is recommended for a Phase II effort.

Low Speed (60,000rpm) Grinding of Steel:
In order to compare with the results obtained through grinding with the high-speed spindle, several grinding tests were performed on the Ultra-Machinable 12L14 Carbon Steel using the standard 60,000rpm spindle at Georgia Tech. The grinding wheel used was the same as that used in high-speed grinding tests (0.030" diameter (762µm), 240 grit CBN abrasive, electro-plate bonding Di-coat grinding wheel). The test matrix used is shown in Figure 6 below:

TEST	DOC (μm)	Feed (mm/min)	Speed (rpm)
1	20	1	60,000
2	20	2	60,000
3	20	3	60,000
4	30	1	60,000
5	30	2	60,000
6	30	3	60,000
7	40	1	60,000
8	40	2	60,000
9	40	3	60,000

Figure 6 – Test Matrix used for low-speed grinding of steel at Georgia Tech.

Cutting forces were measured in the x (feed) and y (depth of cut) directions and the results are shown in the plots in Figures 7 and 8 below.

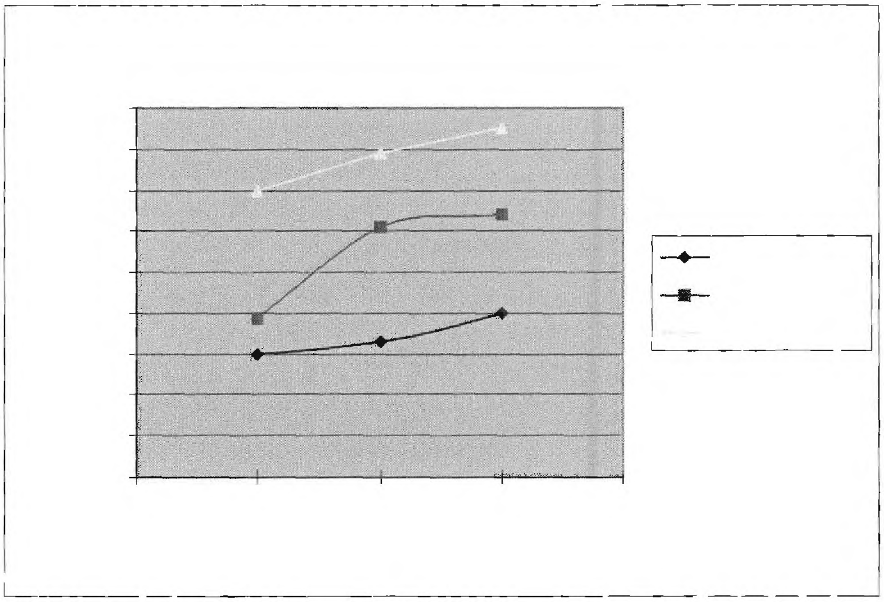


(a)

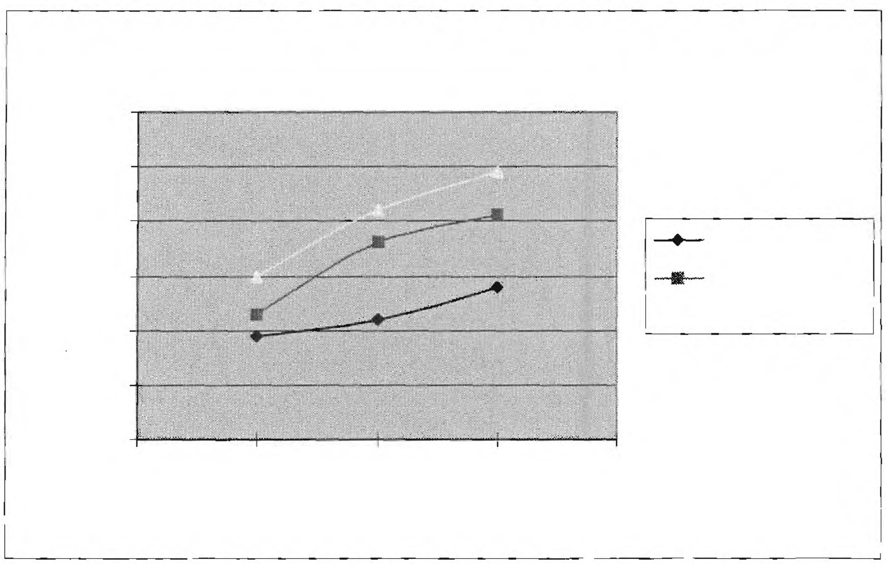
(b)

(c)

Figure 7 – Fx and Fy plotted versus Feed Rate in low-speed (60,000rpm) grinding of Steel at depths of cut of (a) 20um, (b) 30um, and (c) 40um.



(a)



(b)

Figure 8 – (a) Fx plotted versus Feed Rate for depths of cut of 20um, 30um, 40um in low-speed (60,000rpm) grinding of Steel, and (b) Fy plotted versus Feed Rate for depths of cut of 20um, 30um, 40um in low-speed (60,000rpm) grinding of Steel.