COMPARISON OF MACHINING SIMULATIONS FOR 1045 STEEL TO EXPERIMENTAL MEASUREMENTS

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ABSTRACT

This paper compares model-based simulations to experimental measurements obtained under the Assessment of Machining Models project at the National Institute of Standards and Technology. Validation of models and simulations under this project rely on measurements from carefully conducted benchmark machining tests performed under a broad range of machining conditions using American Iron and Steel Institute (AISI) 1045 steel. This paper focuses on comparing finite-element model simulations to the benchmark test data and discussion of limitations of experimental measurements and simulations in capturing process behavior. Cutting forces, temperatures, and chip dimensions predicted through simulation are compared to measurements of these variables from the Assessment of Machining Models benchmark test data.

INTRODUCTION

Despite the economic and technical importance of machining processes, machining remains poorly understood. Machining parameters for industrial practice are chosen through empirical testing and the experience of machine operators and programmers. This process is expensive and time-consuming. Furthermore, while large empirical databases have been compiled [1,2] to aid process design, databases lose relevance as new tool materials, machines, and workpiece materials are developed. For example, developments in high-speed machining centers and new tool materials over the past ten years have resulting in an order of magnitude increase in machine capabilities for cutting speeds and feed rates and new tooling achieves useful tool life levels for many materials under these conditions. These developments have rendered databases and handbook tables essentially useless for effective use of modern equipment.

An alternative approach to empirical testing and experience is the *development of predictive models* that are based upon the fundamental physics of the machining process. The advantage of this approach is that predictions are made from the basic physical properties of the tool, workpiece materials, and kinematics/dynamics of the process. Thus, after the appropriate physical data is determined, the effect of changes in cutting conditions (e.g., tool geometry, cutting parameters, etc.) on industrially relevant decision criteria (e.g., wear rate, geometric conformance, surface quality, etc.) can be predicted without new experiments. If robust predictive models can be developed, this approach would substantially reduce the cost of gathering empirical data and would provide a

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platform for *a priori* optimization of machining process parameters based upon the physics of the system.

The difficulties in realizing true predictive models for machining arise from the extreme physical phenomena inherent in the system. Machining generates a highly inhomogeneous plastic flow where highly localized stresses generate high rates of plastic deformation (up to 10^6 s^{-1}) that give rise to high gradient thermal fields (1000 ºC/mm), high temperatures (1200 ºC in machining steel), high temperature rates (1000 ºC/ms), and high pressures (10 MPa). This type of complex plastic flow is difficult to predict even with sophisticated numerical software, and the basic data on material behavior under such conditions is unavailable for most materials of practical interest [3,4]. These difficulties have forced model development to rely on various levels of empirical input data taken from machining tests in order to model process variables of industrial interest. The limitations imposed on the applicability of machining models from their reliance on empirical input data has limited their industrial use, particularly in smaller operations which are unable or unwilling to perform extensive validation testing.

The intent of the Assessment of Machining Models (AMM) project [5,6] is to provide an unbiased and anonymous assessment of the ability of current machining models to predict the practical behavior of machining processes. We made no attempt to restrict the definition of a model, other than to state that models should be clearly defined in terms of the input data needed to make a prediction. For the purposes of the AMM project, we define a correct prediction as one that agrees with an experimental result to within a well-quantified experimental uncertainty. The intent is to generate an experimental data set encompassing the inherent uncertainties associated with multiple laboratories and machining centers, provide an unbiased report of current capabilities for predicting the practical behavior of machining operations, and develop a roadmap for future directions in machining modeling research.

From the industrial point-of-view, it is important that approximate predictions made from machining parameters typically available on the shop floor are more useful than precise predictions based on less readily available model parameters. However, critical assessment of model performance and robustness is necessary before such models can see widespread industrial use. Any meaningful assessment of model performance must have two characteristics: first, it must be based upon an accurate assessment of the uncertainty inherent in machining operations, and second, predictions must be conducted blindly with the predictor having no *a priori* knowledge of the test results.

This paper presents a comparison of simulation results from a finite element model-based software package to the AMM benchmark data set and offers related remarks on the accuracy of the simulation. The benchmark data set is available from the project web site at http://www.nist.gov/amm/ [7]. The data set is distributed as a zip file containing individual text files for each variable measured in each experiment, summary files with chip measurements and averages from the text files, as well as micrographs and interferograms of worn inserts. This paper focuses on comparisons of simulation results to the information in the summary files for selected experiments from two of the four laboratories that contributed to the AMM benchmark data set.

BENCHMARK DATA SET

The cutting process chosen for the AMM project was orthogonal machining of American Iron and Steel Institute (AISI) 1045 steel using a general purpose tungsten carbide / cobalt (WC/Co) unalloyed carbide grade insert. The chemically simplest grade of carbide was chosen to simplify modeling tool-material behavior based on the material chemistry. Both uncoated and titanium nitride (TiN) coated inserts were used. The AISI 1045 workpiece material was obtained from a single batch/heat of bar stock. The 30.5 m (100 ft) of 101.6 mm (4 in) diameter material arrived in 5 rods, each 6.1 m (20 ft) long. A 50.8 mm (2 in) thick circular sample was removed from both ends of each of the 5 rods. The ten samples were subjected to chemical and metallurgical analysis using American Society for Testing and Materials (ASTM) test procedures E3-95, E407-93, E112-95, E1019-94, and E415-95a [8]. Grain sizes were measured quantitatively using an optical microscope. Additionally, Brinell hardness measurements were performed on a sampling of the material. The material was machined to produce tubes at NIST and then distributed to the three other laboratories. The dimensions of the tubes were 152.4 mm total length, 101.6 mm diameter and tube wall length, and 1.6 mm wall thickness.

The chemical content did not vary significantly among the ten samples. The material conforms to the military specification (milspec) for AISI 1045, and satisfies the more stringent ISO C45 [9] standard except for copper content, which is slightly high. Four representative pictures of longitudinal and transverse cross-sections from two of the samples are shown in Figure 1. Brinell Hardness measurements were performed on two of the 150-mm long workpiece bars with a 29.4 kN load and 10-mm ball. For each of the bars, six measurements were made on one face approximately 1 cm away from the center of the face in a circular pattern around the center. The diameters of the resulting impressions left on the bars were measured at 4.3 mm each with a measurement precision of ±0.025 mm. This equates to a Brinell Hardness Number (BHN) with a ±2s expanded uncertainty of 196 ±5 [10]. The results of the chemical analysis, and hardness tests establish that the original material was mechanically and chemically suitable for use in the machining tests.

The experiments in the benchmark data set comprise a matrix of four variables with two values each. The variables and nominal values in the matrix are rake angles of –7 degrees and + 5 degrees, K68 carbide tool material in uncoated and KC9010 coating, cutting speeds of 200 m/min and 300 m/min, and feeds of 0.15 mm and 0.2 mm, resulting in the listing of tests given in Table 1. Two repetitions of each test condition were performed. For each of these tests, force measurements were taken with a 3-axis dynamometer, temperature measurements were taken using an intrinsic work-tool thermocouple circuit [11] at three of the four laboratories, and chip dimensions were taken with calipers for one of the four laboratories. The raw data was averaged over time, and the resulting averaged measurements of force and chip thickness for one repetition of the experiments from laboratory #1 are given in Table 2. The forces and work-tool thermocouple voltages for one repetition of the experiments from laboratory #3 are given in Table 3. An example of typical raw data for cutting and thrust forces is given in Figure 2. This example comes from test 4, laboratory #3.

Test	Cutting Speed (m/min)	Feed (µm/rev)	Rake Angle	Tool Coating
1	200	150	-7	None
2	200	150	+5	None
3	200	300	-7	None
4	200	300	+5	None
5	300	150	-7	None
6	300	150	+5	None
7	300	300	-7	None
8	300	300	+5	None
9	200	150	-7	KC9010
10	200	150	+5	KC9010
11	200	300	-7	KC9010
12	200	300	+5	KC9010
13	300	150	-7	KC9010
14	300	150	+5	KC9010
15	300	300	-7	KC9010
16	300	300	+5	KC9010

Table 1: Parameters for orthogonal cutting tests for benchmark data set.

Test	Cutting Force (N)	Thrust Force (N)	TC Voltage (V)	Thickness (mm)
1	607	500	0.48	0.493
2	583	402	7.43	0.424
3	1125	740	3.48	0.759
4	976	493	6.51	0.734
5	623	478	13.61	0.546
6	539	326	9.78	0.389
7	1045	628	2.39	0.668
8	888	406	5.30	0.709
9	592	467	1.74	0.386
10	534	355	3.15	0.391
11	1095	700	0.88	0.704
12	929	445	2.00	0.653
13	569	420	0.48	0.394
14	512	290	7.43	0.325
15	999	584	3.36	0.658
16	875	358	1.29	0.602

Table 2: Average Experimental Measurements from AMM Laboratory One.

While the intrinsic work-tool thermocouple method has been used for some time in experimental research [11-14] it has the following documented shortcomings: (1) it reports a weighted integration of the temperatures across the tool-chip interface surface; (2) it is affected by other bi-conductor interfaces in the measurement loop; and (3) it is affected by (unknown) fluctuations in tool-chip contact area. Nonetheless, this method remains one of the most robust and reliable methods for assessing changes in mean tool-chip interface temperatures. Unfortunately, signals measured through any of the coated inserts were not found to be sufficiently consistent to be a meaningful representation of the average temperature at the tool-chip interface surface.

Test	Cutting Force (N)	Thrust Force (N)	TC Voltage (V)	Thickness (mm)
1	622	488	12.23	n.a.
2	569	379	12.61	n.a.
3	994	560	13.17	n.a.
4	931	463	13.49	n.a.
5	620	452	14.68	n.a.
6	517	306	13.89	n.a.
7	1042	616	12.02	n.a.
8	824	360	14.69	n.a.
9	554	371	2.00	n.a.
10	540	346	1.95	n.a.
11	992	546	0.21	n.a.
12	933	465	1.47	n.a.
13	544	345	1.66	n.a.
14	513	304	2.30	n.a.
15	839	404	5.50	n.a.
16	790	361	1.86	n.a.

Table 3: Average Experimental Measurements from AMM Laboratory Three.

FINITE-ELEMENT SIMULATIONS

The finite element model-based simulations were performed using a finite element model-based machining simulations software package. Parameter values for the simulations were selected in accordance with the values used during the AMM experiments as given in Table 1. For simulation options, default values were selected except for some of the meshing parameters.

The time required to run simulations is very sensitive to the total number of mesh elements in the finite-element model. One of the strengths of adaptive meshing is the ability to dynamically redefine the finite element mesh during the simulation in order to introduce more elements where needed and remove elements that are not needed. The primary limiting factor in how few mesh elements can be used without creating unacceptable results is the ratio between the minimum mesh element size and the cutting edge radius of the tool. Due to the very small 0.002 mm edge radius of the uncoated K68 carbide inserts, a larger tool edge radius of 0.01 mm was used for the simulations to keep the number of mesh elements manageable. The minimum mesh element size needed to be reduced from the default value of 0.02 mm to 0.006 mm. Furthermore, the length of the workpiece was reduced from the default value of 5 mm to 3 mm and the length of cut was reduced from the default value of 3 mm to 2 mm. For consistency, the same dimensions and mesh parameters were used for the simulations with the KC9010 coated inserts, even though their edge radius (0.03 mm) was much larger.

Results from the simulations were analyzed in a manner very similar to the analysis of the measurements from experiments. The cutting forces were time averaged over a steady-state region to obtain single values for the cutting and thrust forces for each simulation. The chip thickness was extracted from the final results frame of the simulation at the location where the chip leaves contact with the rake face of the tool. The temperatures reported in this paper are the final peak tool temperature of the simulation. The forces, temperatures, and chip thickness for the sixteen simulations are given in Table 4. As an example of typical raw simulation results, cutting and thrust forces for the simulation of Test #4 are shown in Figure 3, and the corresponding simulated temperature profile is given in Figure 4.

Test	Cutting Force (N)	Thrust Force (N)	Temp (°C)	Thickness (mm)
1	615	225	590	0.245
2	540	100	560	0.245
3	1100	370	640	0.49
4	980	140	600	0.46
5	630	230	645	0.235
6	540	100	620	0.245
7	1040	355	700	0.51
8	970	140	660	0.455
9	665	352	656	0.235
10	585	245	640	0.235
11	1150	475	725	0.45
12	1090	290	675	0.495
13	665	360	740	0.238
14	585	255	715	0.245
15	1100	490	835	0.55
16	1100	300	720	0.48

Table 4: Average Simulation Output Values from Finite Element Simulation.

COMPARISON OF SIMULATIONS TO EXPERIMENTS

Due to various factors in conducting the experiments, there is considerable variation in the measurement results from one laboratory to another. As such, some degree of judgment has been exercised in selecting individual laboratories for comparing results of particular measured variables to the simulation results. The chip measurements were only performed on the chips from laboratory #1, so the chip measurements from laboratory #1 are used for comparison to the simulations. The work-tool thermocouple measurements from laboratory #3 exhibit the most consistent behavior in comparison to prior published results and in terms of general expected trends, so simulation temperatures are compared to the thermocouple measurements from laboratory #3. The force measurements from laboratory #1 and #3 are very similar, so that comparison of simulations to either is similar. Force comparisons are made between the simulations and laboratory #3 since the trends in temperature measurements will be compared to the intrinsic thermocouple measurements for laboratory #3. Since the thermocouple measurements are voltages and not temperatures, temperature estimations are projected based on an assumption of a linear relationship between voltage and temperature over the measurement range with a scale determined by the average ratio of simulated temperature to measured voltage. This enables comparison of trends in the thermocouple measurements to trends in the simulated temperatures with respect to changing cutting conditions. However, there is no assurance that the magnitudes of the simulated temperatures or measurement-based estimates are consistent.

For simplicity, comparisons of measured variables from experiments and simulated values of each variable (forces, temperatures, and chip thickness) are presented separately for coated and uncoated inserts. The cutting forces and thrust forces for experiments and simulations for coated and uncoated inserts are presented in Figures 5 and 6. As can be seen in Figure 5, the agreement between the simulated and measured cutting forces for the uncoated inserts is quite good. In fact, the agreement of the cutting forces is better than the agreement between some of the laboratories for the complete AMM benchmark data set. The thrust forces, however, are consistently low by 35% to 65%. Trends in the changes in thrust forces for each of the individual simulations are somewhat consistent with the trends in changes in measurements.

The temperature estimations based on the measured intrinsic thermocouple voltages for the uncoated inserts and the corresponding simulated temperature values are given in Figure 7. Comparisons of temperatures for the coated inserts are not included due to the inconsistency of the intrinsic thermocouple measurements for those experiments. The agreement in the trends of changes in temperature with cutting conditions to changes in thermocouple voltages is excellent for most of the cutting tests, but tests one and three are about 8% higher and test seven is about 23% higher. The chip formation for test seven is highly segmented, which may provide some explanation for the large difference. The simulated temperatures shown are the final peak tool temperature during the simulation, while the thermocouple measurements represent some form of an average of the electrical potential generated across the entire area where the tool contacts the chip and the workpiece [9]. It is therefore expected that there would be some differences between trends in the thermocouple measurements and trends in the simulated temperatures.

Finally, the measured and simulated chip thickness values for the coated and uncoated inserts are shown in Figure 8. The primary source of changes in chip thickness for the changes in cutting parameters in the benchmark data set is the factor of two increase in the feed. In the order of the test numbers, each subsequent pair represents a change in feed from 0.15 mm to 0.3 mm and back, so that tests 1 and 2 are at 0.15 mm feed, tests 3 and 4 are at 0.30 mm feed, tests 5 and 6 are at 0.15 mm feed, and so on. The trends in chip thicknesses follow this pattern fairly closely for both the measurements and simulations, but the simulations are consistently lower than the measurements. This difference is most likely related to the consistently lower thrust forces. Changes in cutting speed and rake angle do not have a strong effect on chip thickness, and both measured and simulated values of chip thickness reflect this.

DISCUSSION

Measurements from experiments can vary due to factors that are difficult to control, such as workpiece misalignment, material inhomogeneity, and inconsistent tooling. The AMM experimental plan went to great lengths to address these and other sources of variability. With further effort, it may have been possible to improve the agreement between results from different laboratories by requiring additional precautions. The primary precaution that we would advise is based on our experience, and would be the use of custom turned soft jaws in the chuck of the machine tool for mounting the workpieces. Since the workpieces had to be machined without a tailstock and the tube walls were too thin to allow for significant adjustment of the workpiece position once it was in the chuck, it is apparent from the raw force data that some of the workpieces were off center during the experiments. Furthermore, there are strong correlations between the rotational frequency of the workpiece and the frequency of variation of the force signal for most of the tests. This is to be expected to some degree, but some of the force variations were nearly the same magnitude as the average cutting forces. As such, it is not surprising that the lab-to-lab variation in forces is high.

Another important factor in obtaining consistent results is the performance of the tooling. Differences in the rate of wear for different tools will lead to significant differences in measurements of cutting forces, temperatures, and chip thickness. While the AMM tests were conducted with nominally identical tooling, higher levels of consistency could be obtained through performing many repetitions and rejecting those that that showed significantly higher levels of wear. For the tests with high cutting speed, the inserts did show signs of wear that would affect measurements.

Under some conditions, finite element model-based simulations can have significant sensitivity to relatively small adjustments of a variety of parameters, including material properties, mesh element size, friction conditions, and tool edge radius. While nominal values for material properties and the tool edge radius were determined before the experiments, they were not determined for every workpiece and every tool edge. Since the simulations all used nominal values, any differences between the actual values used in the experiments and the nominal value used in the simulations will create differences between the results of the measurements and simulations. The inserts from the experiment were marked and retained, so it would be possible to perform further measurements to assess the state of wear of the inserts at the end of the cutting tests. Simulations could then be performed based on the worn geometry for further comparison. Performing simulations to determine the sensitivity of simulation results to these parameters is beyond the scope of this paper, but could be the subject of further research.

Determinations of the mesh element size and friction conditions are not based directly on experimental conditions or measurements, but rather the user’s judgment of what is appropriate. The friction coefficients were left at their default values. Increasing the friction coefficient led to a moderate increase in the forces and temperatures. The actual friction conditions at the tool-chip interface are somewhat dependent on the machining conditions, so it might be possible to attain better agreement between measurements and simulations by adjusting the friction coefficient. Without an appropriate measure of how to adjust the friction coefficient, adjustments do not have a firm basis.

The nominal cutting edge radius was so small for the uncoated cutting tools that the minimum mesh element size would have to be smaller than a micrometer. Simulations with this mesh element size would take so long to run that they would make the study impractical. Since a larger cutting edge radius was used in the simulation in order to allow a more practical minimum mesh element size, it is not surprising that the measurements of cutting forces and chip thickness are not in perfect agreement with the simulations. A larger edge radius would be expected to lead to larger thrust forces, but the forces in the simulation results are smaller than the corresponding measurements. The thrust force depends strongly on the friction coefficient, so adjusting the friction coefficient might lead to better agreement between the results from the measurements and the simulations.

CONCLUSION

This paper presents a comparison of finite element model-based simulations of orthogonal machining of AISI 1045 steel to a carefully constructed benchmark data set. The agreement between the simulation results and the measurement results is varied. The cutting forces and trends in temperatures are in excellent agreement for most of the tests, while the thrust forces and chip thickness measurements are significantly larger than the simulation results. A variety of reasons for less than perfect agreement between the measurements and simulations are discussed, including limitations of experimental measurement capability, experimental control, simulation resolution, and material information.

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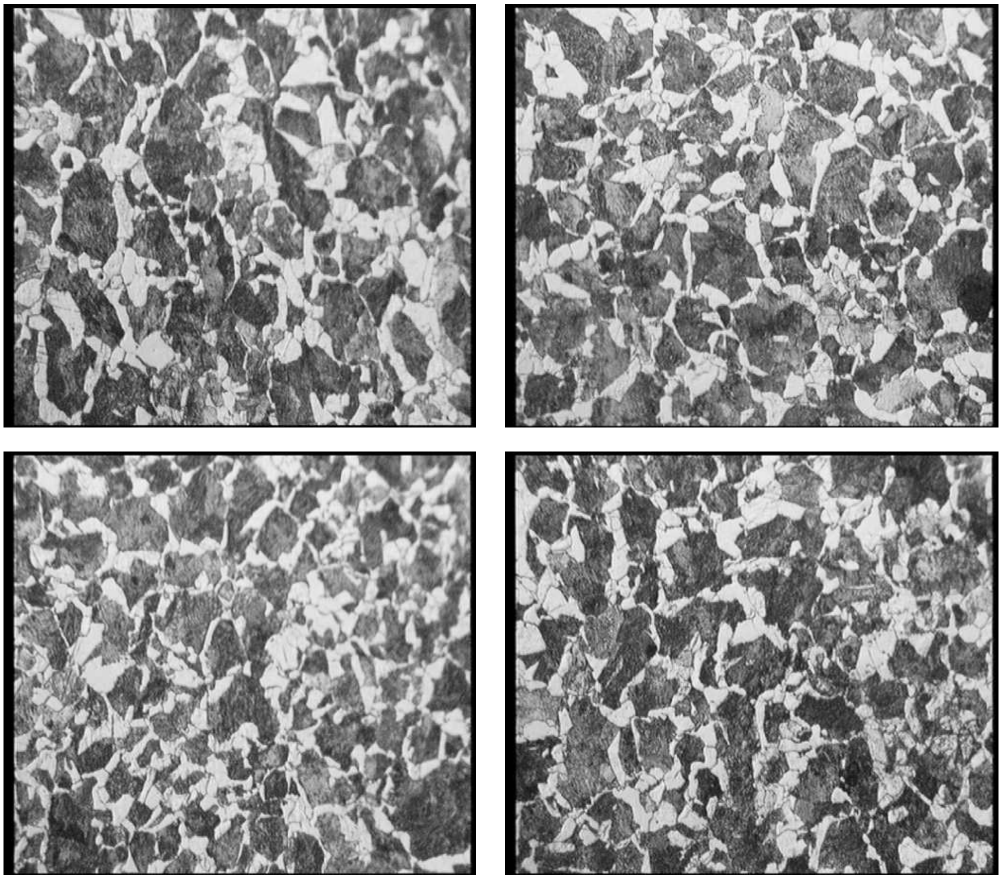

Figure 1: Micrographs of polished and etched longitudinal and transverse sections of bars

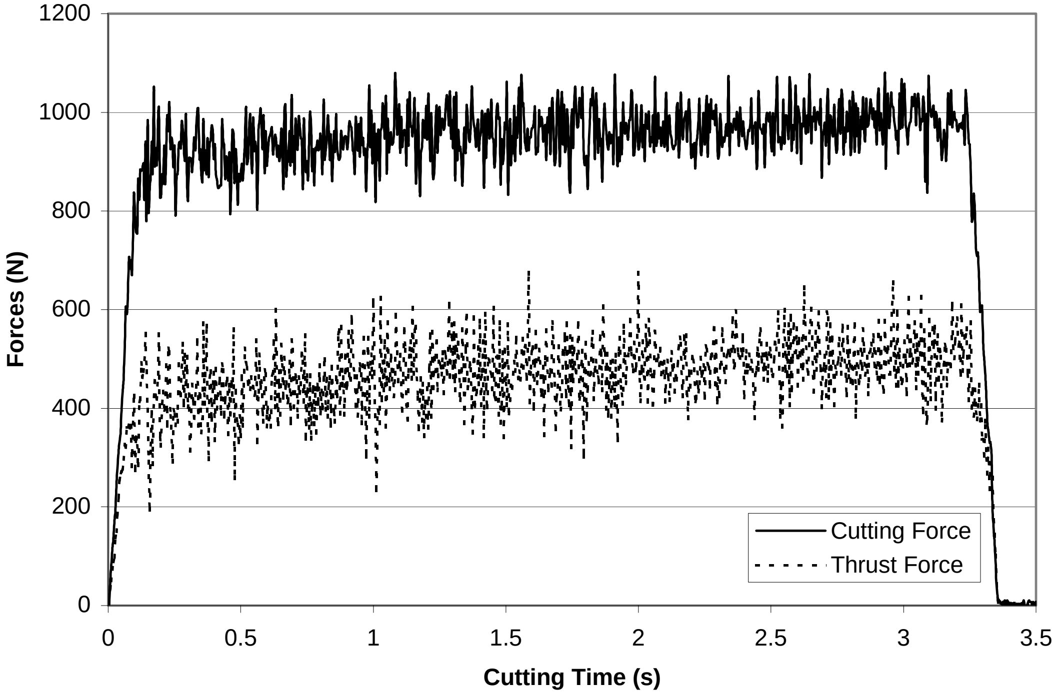

Figure 2: Raw Cutting and Thrust Force Data from Test 4, Laboratory 3.

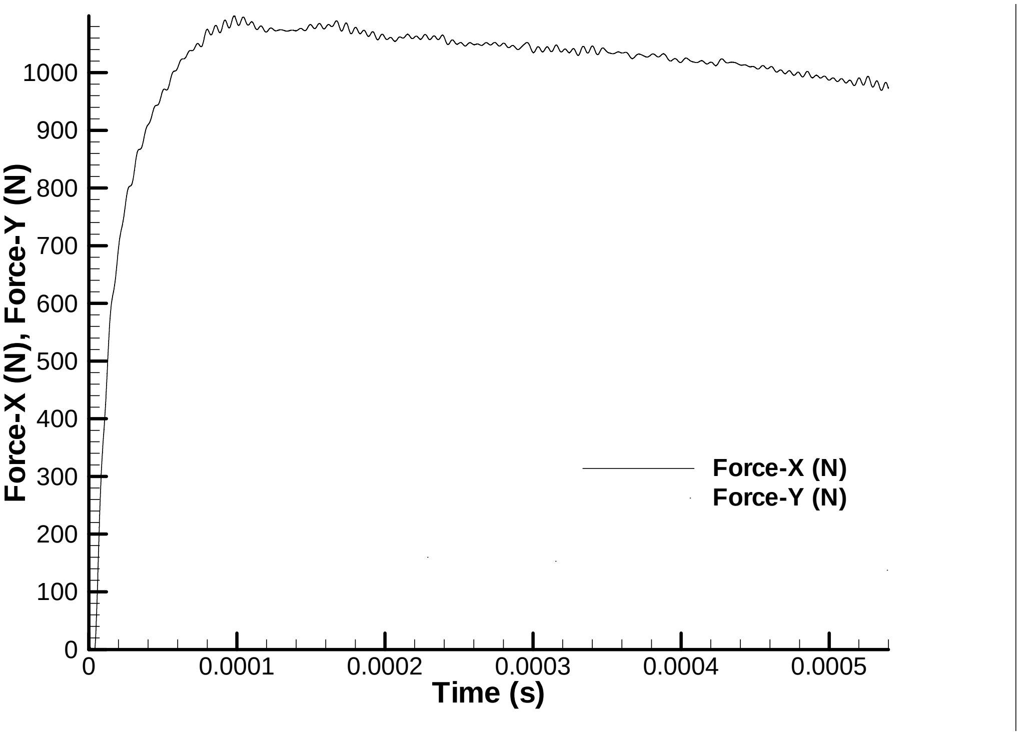

Figure 3: Simulated Cutting and Thrust Forces for Simulation 4.

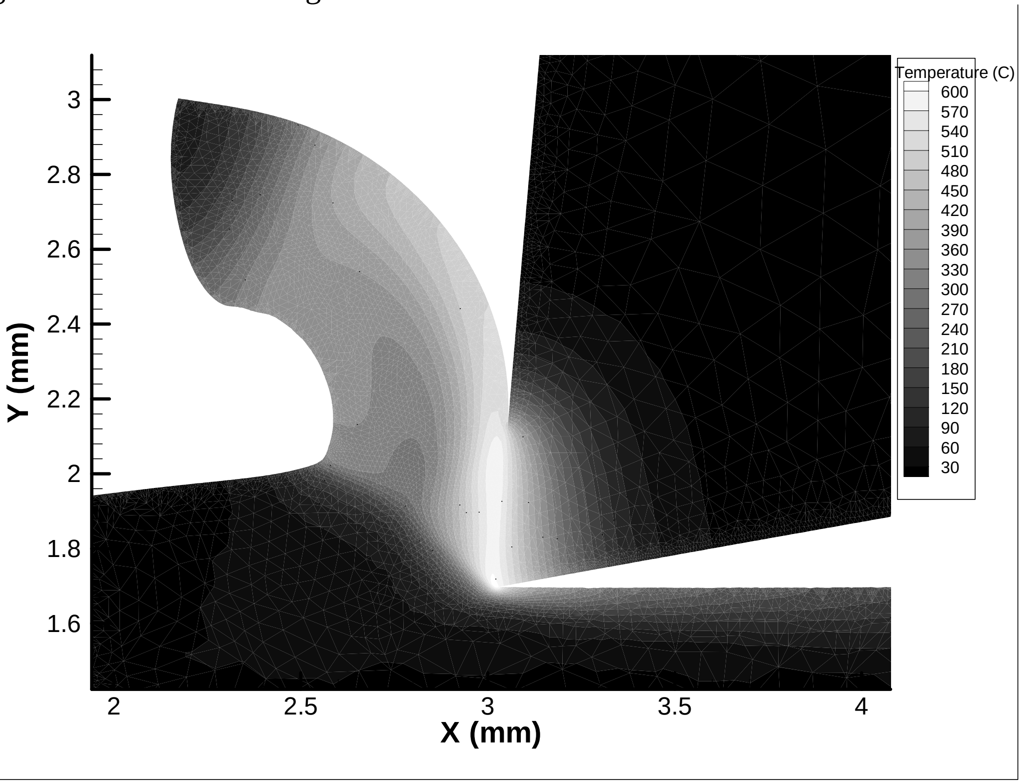

Figure 4: Simulated Temperature Profile for Simulation 4.

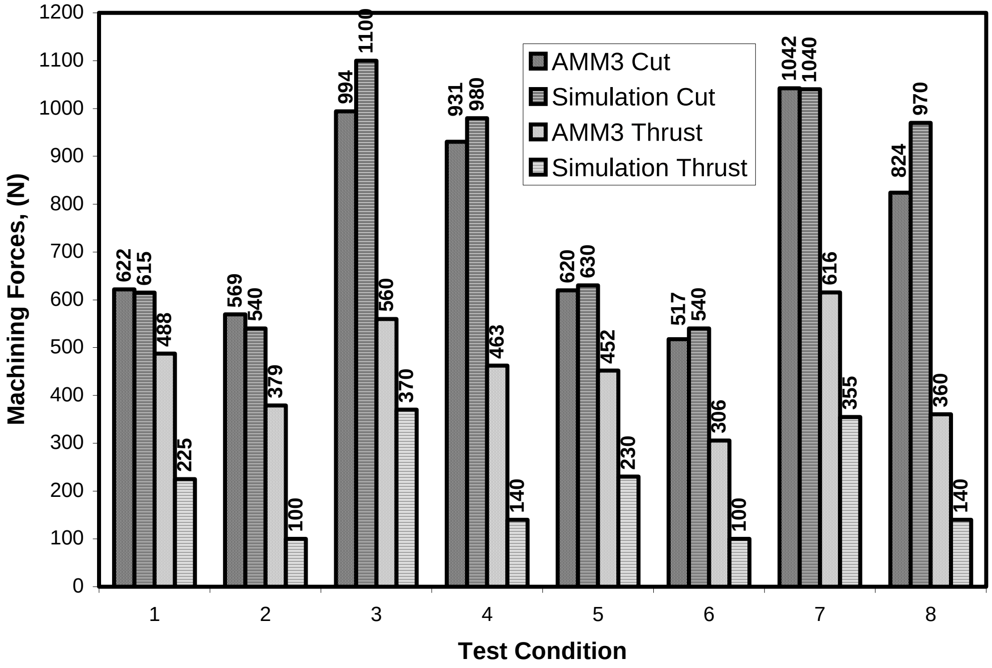

Figure 5: Comparison of Cutting and Thrust Forces for Uncoated Inserts

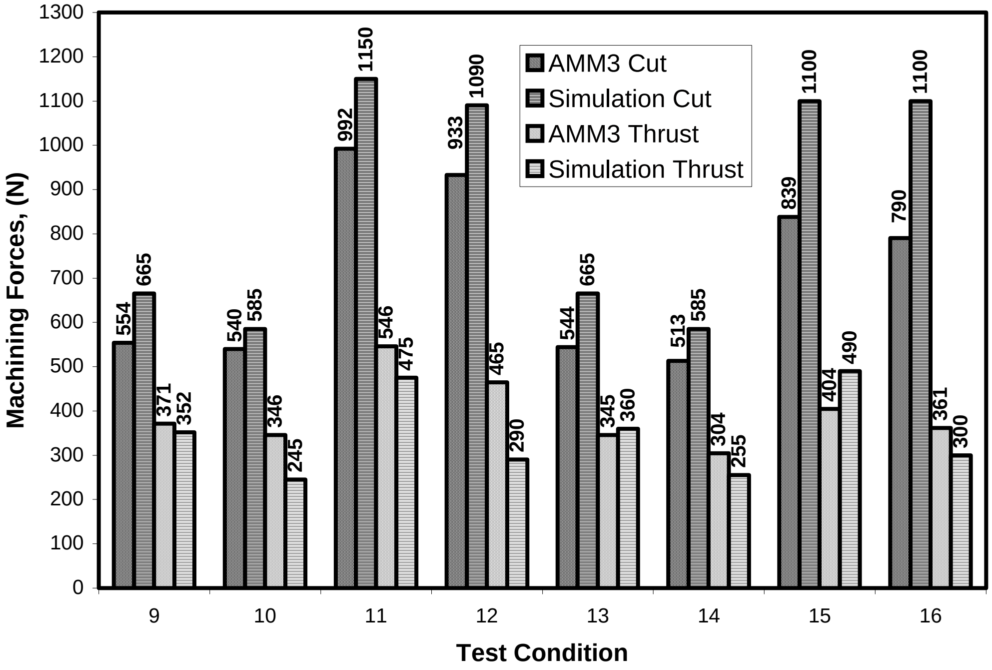

Figure 6: Comparison of Cutting and Thrust Forces for Coated Inserts

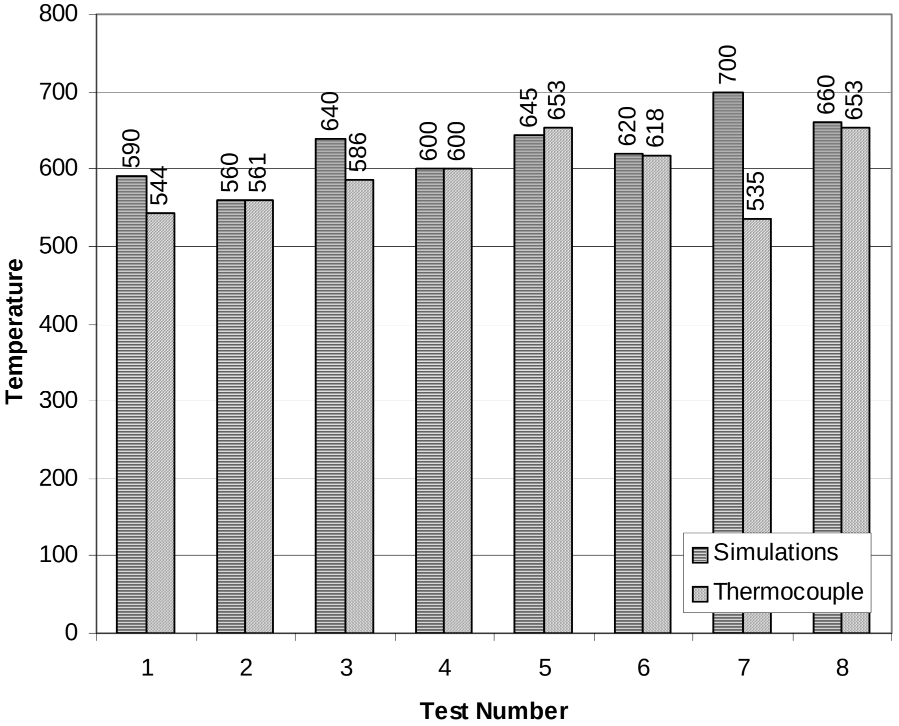

Figure 7: Comparison of Measured Intrinsic Thermocouple Voltages and Simulated Peak Tool Temperatures

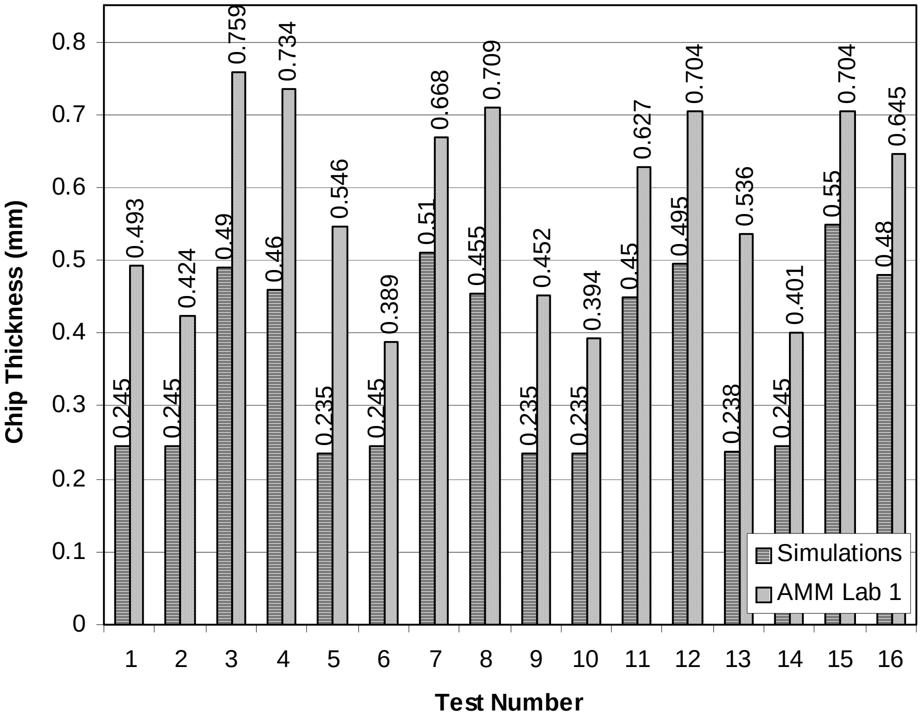

Figure 8: Comparison of Chip Thickness