

DYNAMIC MATERIAL PROPERTIES FOR MACHINING SIMULATION USING THE NIST PULSE-HEATED KOLSKY BAR

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Abstract

The modeling or simulation of machining processes is important for economically implementing new manufacturing processes such as high-speed milling or ultraprecision machining. Knowing if a process will provide the required output prior to investing in expensive equipment is vital. All machining process models, including those for ultraprecision processes, are dependent on knowing the appropriate material properties. The NIST pulse-heated Kolsky bar is an experimental apparatus built for measuring the dynamic material properties at elevated temperatures useful in machining models. Stress-strain curves for AISI 1045 steel obtained at strain rates of over 2000 /s and high temperature (over 900 C) are presented.

1. Introduction

The need to improve machining processes has been obvious to machine shop workers for hundreds of years. Great strides in optimizing processes have been accomplished by many generations of machinists who boldly varied parameters and implemented improvements based on their direct experiences. Early manufacturing researchers realized that it would be extremely useful if one could calculate important parameters, such as cutting forces and tool temperatures, by plugging into a formula. However, it was recognized that material removal processes are extremely complicated and that scientific research was necessary. Some of the early attempts at understanding machining from a scientific standpoint were Ernst [1] and Merchant [2] in the first half of the twentieth century. Then by the 1970s, hundreds of research papers had been published. Several different historical surveys, for example Komanduri [3], summarize much of this work. A variety of detailed methods were developed and presented, but by the late part of the century it appeared that the most promising analytical method of predicting machining process parameters was the finite element modeling (FEM) method. Some of the earliest work of applying the FEM method to machining research came from the precision engineering community, with work by Strenkowski at North Carolina State in the 1980s [4].

The FEM method can be used to examine the effects of different tool geometries and parameters, such as cutting speeds and feeds. Detailed and user-friendly codes have been developed; for example, work presented by Marusich [5] describes an approach that is used in a commercial code.* Temperature profiles can be calculated as part of the FEM approach for even the small depths of cuts used in the ultraprecision machining processes, such as diamond turning, with virtual spatial resolution well beyond what can be physically measured. Even though it is easy to scale the geometry to the small depths of cuts by the FEM approach, there are still many unanswered questions concerning the capability of the models to handle the physics of small depths of cut. Research into the size effects for machining process modeling will continue and this future work will be very important to the precision engineering community. FEM modeling will undoubtedly contribute to the advancement of ultraprecision machining in the future as it is currently contributing to the improvement of more conventional machining processes.

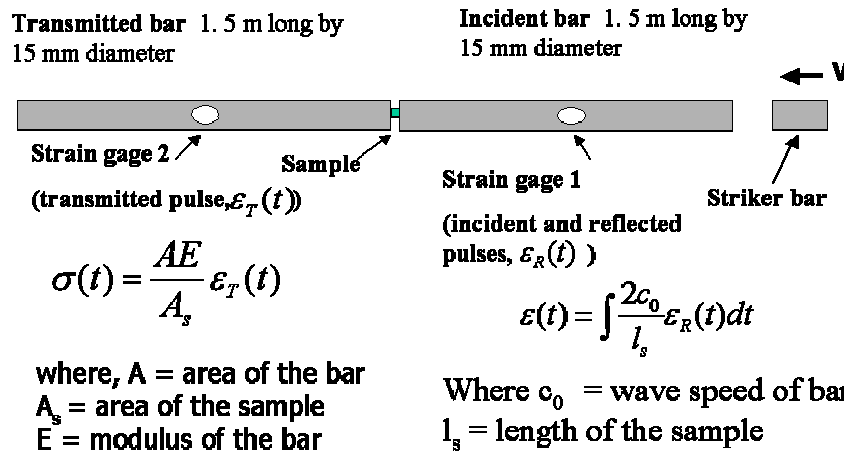
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An essential part of FEM methods is a material constitutive model that relates stress to strain. FEM codes have the advantage of being able to handle complicated representations of the constitutive model that include the high strain, high-strain rates, high temperatures, and high-heating rates found in machining processes. An FEM analysis with many elements can involve a very large number of relatively simple calculations. With modern fast computers, realistic geometries and complicated constitutive relationships can be handled in reasonable times. Practical difficulties arise in applying the FEM approach because the necessary constitutive models are not readily available for materials often required in modern manufacturing. Also, the accuracy of the FEM results are often limited by not being able to accurately describe the constitutive behavior of the material under the conditions found in real machining processes.

2. The NIST pulse-heated Kolsky bar apparatus

To assist in ongoing efforts to provide constitutive model data needed for FEM codes to adequately simulate machining processes, we have built a new facility at the National Institute of Standards and Technology (NIST). This facility is based on a well-established method for obtaining high-strain-rate stress-strain curves called a Kolsky bar (or split Hopkinson pressure bar, see the ASM Handbook articles by Follansbee [6] or Gray [7].) To this traditional apparatus we have added a unique capability of resistively heating the sample immediately prior to high strain rate testing. The resistive heating is produced by an accurately controlled pulse of DC electric energy delivered to the test sample from a special apparatus developed by the NIST Subsecond Thermophysics Laboratory. The pulse heating system and Kolsky bar apparatus are described in Yoon et al [8] and Basak et al [9], and the construction and alignment of the NIST Kolsky bar was presented at the 2002 ASPE Annual meeting by Rhorer et al [10]. The Kolsky bar can provide compression testing at strain rates from about 500 /s to 10 000 /s

(traditional tension or compression tests can be done at rates from .001 /s to approximately 100 /s).



The operation of the traditional Kolsky bar is outlined in Figure 1. By recording the output of the two strain gages the stress-strain curve for the sample material can be easily determined. The 15 mm diameter by 1.5 m long bars are supported by guide bearings to support and maintain the alignment of

Figure 1. Kolsky bar operation

the bars as in the traditional Kolsky apparatus. In the NIST system the support bearings are all plastic except the center two bearings, which are graphite lined metal bearings. The center two bearings are connected to a DC electric power supply through large welding cables. The 4 mm diameter by 2 mm long sample, sandwiched between the two long bars, is then resistively heated as the current passes through short sections of the bars and directly through the sample. The volume of the sample is less than 0.01 % of the volume of the portion of the bars conducting the electricity to the sample, and therefore the sample heats much more rapidly than the supporting bars.

A test consists of programming a temperature heating pulse (for example set to reach 1100 K) with a heating time from 150 ms to several seconds. The air gun is triggered with an adjustable delay circuit so that the impact test occurs at the end of the heating pulse. In a typical test, the strain wave generated by

the impact of the striker bar compresses the sample in approximately 150 μ s. During the test the sample temperature is monitored by a high-speed pyrometer (with one μ s resolution) and the uniformity of the sample heating is verified by a thermal imaging camera (approximately 3000 frames/s). The strain gage output is recorded on a digital oscilloscope using standard strain gage circuitry calibrated by the parallel resistor method.

3. Results and Discussion

The resulting stress-strain curves from the Kolsky bar tests can be generated using the approach outlined in Figure 1 and the strain gage recordings. Some results of tests on AISI 1045 steel are shown in Figure 2. These curves show the true stress (flow stress) as a function of plastic strain. At lower strains (less than approximately 3 %) the plots are not accurate because the Kolsky bar technique is not a useable test for determining the elastic modulus of the material but determines plastic strains up to 20 % or more. The upper three curves are from tests at room temperature (without a heating pulse) and illustrate the effect of strain rate on the flow stress. In general, the higher the strain rate, the higher the flow stress.

The flow stress at elevated temperatures is lower (thermal softening) as shown by the two lower curves in Figure 2. For example, the curve labeled Test 305 was a test where the sample was heated to 620 C in approximately 700 ms (a heating rate of approximately 900 K/s) and then held at the temperature for 50 ms prior to the impact. Ongoing and future work will look at additional temperatures and heating rates as well as the repeatability of the tests for the steel samples. In addition future work will include expanding

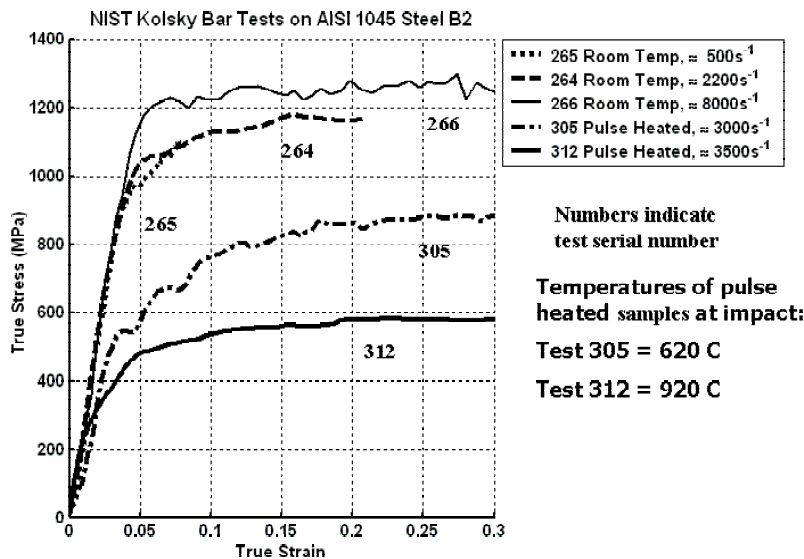


Figure 2. Results of Pulse-heated Kolsky bar tests.

the testing efforts to other materials of interest in machining simulation. Standardizing some of the methods for testing and data reporting of the dynamic material properties are also being investigated as part of this project.

One of the questions that can be addressed with the NIST pulse-heated Kolsky bar, which is not possible with more conventional furnace type heating of the sample, is the effect of heating rate on the stress-strain curves. If the heating rate is fast enough, microstructure changes will not have time to occur prior to the large deformation caused by the impact and rapid compression of the sample. Therefore, in the case of rapid heating the thermal softening should be less than the case of heating to the same temperature but at a slow heating rate. Preliminary high-strain-rate (~ 4000 /s) stress-strain data for AISI 1045 steel samples heated to above 900 C in 250 ms (a heating rate of ~ 3600 K/s) indicate a higher flow stress (~ 200 MPa higher) than samples heated to the same temperature in approximately 2.5 s (~ 360 K/s rate). Additional tests are being performed to further examine and verify the heating rate effect.

4. Conclusions

Process modeling has become an essential component in modern manufacturing enterprises. To develop reasonable models for the machining processes it has been necessary to develop a means of measuring dynamic properties of the materials being machined. Because machining processes involve both high strain rates and high heating rates, the NIST pulse-heated Kolsky bar has been developed as a system to measure these material properties and to provide a test bed for materials research. Using the new pulse heated Kolsky bar apparatus we have demonstrated that stress-strain curves for strain rates from 500 /s to 8000 /s can be generated with a sample temperature of over 1100 K and heating rates of over 5000 K/s immediately prior to the mechanical tests. Work is continuing to expand these ranges of strain rates and heating rates to more completely cover the range of parameters found in machining.

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