CONSTRUCTION AND ALIGNMENT OF A KOLSKY BAR APPARATUS

Richard L. Rhorer, Matthew A. Davies*, Michael D. Kennedy, Brian S. Dutterer, and Timothy J. Burns
National Institute of Standards and Technology
Gaithersburg, MD 20899
*University of North Carolina, Charlotte, NC 28223-0001

Introduction

There is great interest in modeling machining processes to aid in the selection of optimum tooling and cutting parameters in modern manufacturing facilities. Implementing machining process models is often limited by not having appropriate material properties for the work piece material. This is complicated by the fact that most of the material data available is from tests performed at low strain rates and at room temperature, whereas the machining processes involve very high strain rates and very rapid heating of the material in the cutting zone. The relationship of stress to strain (how much a material deforms under a given load and often referred to as the stress-strain curve or constitutive material model) at high strain rates and high temperatures can often be very different from the normal “handbook” relationship. Therefore, a vital step in developing and implementing effective machining models is to provide appropriate stress-strain relationships for materials of interest to industry. In 2001, a project was started at NIST – Materials Data and Metrology for Machining Simulation — to obtain and provide to industry such data. The project includes building a unique facility using a traditional Kolsky bar apparatus, combined with a fast pulse-heating capability. The goal is to rapidly heat a material sample with an electrical pulse, and then immediately perform a Kolsky bar compression test, thereby providing high-strain-rate, pulse-heated material response data.

The most widely used method for obtaining high strain rate material data is the split Hopkinson pressure bar, often called a Kolsky bar. This dynamic testing method of impacting a long bar and studying the stress waves produced in the bar was pioneered by Bertram Hopkinson early in the 20th Century. By the middle of the century, H. Kolsky developed enhancements of the Hopkinson method by splitting the bar into two parts, with the sample to be tested sandwiched in between. He demonstrated both analytically and experimentally that the apparatus could be used to obtain high-strain-rate stress-strain curves for materials. Many researchers have made significant contributions to further develop the method; a comprehensive article (including a list of 114 references) by Gray summarizes much of this work.

Although many Kolsky bars have been built in research facilities, and the technique of constructing and operating the bars is fairly well documented, an interesting precision engineering aspect is the method for determining the straightness and alignment of the bars and their supports during construction of the apparatus. The alignment of the bars is important; for example Gray states: “For proper Hopkinson bar operation, the bars must be physically straight, free to move without binding, and carefully mounted to ensure optimal axial alignment.” However, to our knowledge, a quantitative specification for the alignment precision is not given in the literature. The purpose of this paper is to report the approach used at NIST to construct the Kolsky pressure bar system, with particular emphasis on the alignment of the bars. Measurement and documentation of the straightness of the NIST system will be valuable in assessing the effect of straightness on the performance of the system. An ongoing effort of the NIST project will be to correlate the straightness with the performance of the Kolsky bar apparatus.

Modeling Machining Processes

In the introduction to a 1938 paper, Hans Ernst, one of the pioneers in metal cutting research, said:

Over the past few hundred years we have slowly learned to use metal cutting tools without really knowing how they work. We have learned a lot about speeds and feeds, but, in order that we may meet the increasing demands of modern production for greater output and higher quality finish, it is necessary that we obtain a clear understanding of what is taking place at the cutting edge.

We have learned a great deal about machining processes and the physics of what is “taking place at the cutting edge” since the 1930s, but there is still a great deal to learn. By the mid-twentieth century there was a broad effort, both in the U.S. and internationally, to conduct machining research and develop effective models that could guide
manufacturing planners to improved machining processes. With the advent of rapidly expanding digital computing capabilities in the late twentieth century, interest shifted to using modern analytical tools such as the finite element analysis (FEA) method to accurately model the machining process. However, efforts to use the FEA method to model machining processes have been hampered by the lack of adequate material properties data for the high strain rates and rapid heating encountered in machining processes. During the cutting of metals, i.e. machining, rapid heating occurs (on the order of 50,000 K s\(^{-1}\)) up to temperatures on the order of 1300 K at very high strain rates (in the range of \(10^3\) to \(10^6\) s\(^{-1}\)).

The new pulse-heated Kolsky bar apparatus at NIST has been designed and built to produce a high-strain-rate test, while simultaneously pulse-heating the sample with electric current, thereby providing data useful for machining simulations. The pulse-heating capability is part of an existing NIST facility for measuring thermophysical properties of materials. By placing the new Kolsky bar apparatus in the adjacent laboratory, we will take advantage of the sophisticated switching systems and large battery power supplies already in place to heat the sample to temperatures up to 1300 K in sub-second times, and accurately control the temperature prior to the strain wave impact. The system that will be used to pulse-heat and measure the temperature of the Kolsky bar sample is described by Basak, et al.

**Design, Fabrication, and Alignment of the NIST Kolsky Bar Apparatus**

The NIST Kolsky bar apparatus was fabricated in the NIST Shops and assembled in the Special Projects Building. The design was based in part on discussions with researchers at Johns Hopkins University and the Army Research Laboratory, along with published information, such as the articles in the American Society of Metals Handbook. The completed Kolsky bar in the lab at NIST is shown in Figure 1. The apparatus consists of two long straight bars, called the incident and transmitted bars, with a material sample sandwiched between the two bars. The bars are mounted in bearings to allow only pure axial motion. The apparatus includes an air gun to accelerate a striker bar into the incident bar at velocities up to 40 m/s. In operation, the output of the system is the oscilloscope-recorded signals from strain gages (1000 ohm foil gages) mounted in the center of the incident and transmitted bars.

The bar system is mounted on a precision base structure 5 m long, made in five sections. Each section consists of an H-beam (200 mm wide by 225 mm deep), with steel plates welded on the ends. Each section is precision machined on both ends and the top, then bolted together to form a long, straight, wide, flat surface for mounting the bar supports. Two A-frames that have casters and screw pads for leveling support each of the five base sections. The sections can be rolled into place and then bolted together to form the Kolsky bar base structure. The completed base structure can be seen in Figure 1. Instead of using one long beam for the base structure, the base was made in sections that could be wheeled into place individually and then assembled in the laboratory next to the pulse-heating facility. At the time of the assembly, each base section was bolted in place and then the whole assembly precision leveled. After approximately one year, the base structure has

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*Matthew Davies, Brian Dutterer, Richard Fields, Lyle Levine, Timothy Burns, and others from NIST met with K.T. Ramesh at The John Hopkins University, and with Wayne Chen of the University of Arizona and Tusit Weerasooriya at the U.S. Army Research Laboratory in Aberdeen, MD, prior to starting the design of the NIST Kolsky bar.*
proven to be stable and remained level within the resolution of a precision machinist’s level (approximately 40 μm/m.)

On top of the flat-machined surface of the base, 12 bearing support posts are mounted. These support and align the two 15 mm diameter by 1.5 m long bars. Each bearing support post contains an optical type x-y adjustable mount, so that the bearing in each post can be individually adjusted for alignment. The alignment was performed by carefully adjusting an optical tooling scope (K&E Model 71 2030 Alignment Telescope) for a line of sight determined by the air gun barrel using a target in each end of the barrel. This target is a precision brass cylinder machined to have a close fit to the inside bore of the barrel with a 1.5 mm hole drilled in the center. The scope mount adjustments for tip and yaw angle, plus vertical and horizontal motion, were used to bring the scope cross hairs in alignment with the target when placed alternately in each end of the barrel. After the line of sight was established using the targets in the barrel, the line of sight was then used to align each of the bearings in turn without touching the scope mount adjustments. For this alignment step, the scope cross hairs were focused on a precision target placed in each bearing. The bearing mount x-y screws were then used to bring the target center hole to a position centered on the scope cross hairs. This target was similar to the target placed in the barrel to establish the line of sight; however, the cylindrical surface was machined to fit closely into the bearing.

After the individual bearings were precision aligned, the 1.5 m long incident and transmitted bars were slid through the bearings into place. This optical tooling approach has an ultimate precision of “approximately one part in 200,000”, or a pointing uncertainty on the order of one arc second. This would translate into an ultimate straightness of about 25 μm for the support bearings. However, the overall deviation of the bearing centers from a perfect line has been estimated to be on the order of 100 μm when taking into consideration uncertainty sources such as the target fit into bearings and the ability to align crosshairs to the target center hole, plus air disturbances and optical distortions of the scope. The bearings are machined to have a clearance of 75 μm for the 15 mm diameter bars. The bars are fabricated from 350-maraging steel, hardened and centerless ground. The bars are straight within approximately 0.5 mm when placed on the flat surface of a coordinate measuring machine. The bearings of the Kolsky bar apparatus probably do some straightening of the bars and there is a slight drag of the bearings on the bars. We have not yet determined a quantitative way of measuring the effect of this straightening, but one of the ongoing efforts of the project will be to address this question.

**Experimental Results to Date**

A Kolsky bar compression test consists of holding a small sample of the material to be tested between two long steel bars. The first bar, called the incident bar, is impacted on the end with a striker bar fired from a small air gun. The impact produces a strain wave that moves down the incident bar, through the sample, and then into the second bar, called the transmitted bar. The deformations in the sample material affect the strain pulse in the transmitted bar and the strain pulse reflected back into the incident bar. A digital oscilloscope records signals from strain gages mounted in the centers of the incident and transmitted bars. The strain signals recorded as functions of time are then used to calculate a stress-strain curve for the sample material. Although the sample size can be varied, the initial testing has all been with 4-mm diameter by 2 mm thick specimens. Various metals are of interest and will eventually be tested. The initial work has been with AISI 1045 steel (because of its importance in the automotive industry) and copper samples for comparison to published results.

The results of a typical room temperature test are shown in Figure 2. The output from the strain gages is recorded on an oscilloscope (Nicolet model 440) and then transferred to a PC for data reduction and plotting. The strain gage output is calibrated in the normal way, using a precision parallel resistor (Vishay Measurements Group, Inc. gages and precision resistors have been used). The first pulse in Figure 2 is the compression wave arriving at the strain gage in the center of the incident bar. The reflected tension pulse arrives back at the same gage about 300 μs later, very close to the same time the transmitted pulse arrives at the transmitted bar gage. According to the theory underlying the experiment, the reflected pulse is directly proportional to the strain rate, and the transmitted pulse is directly proportional to the stress in the sample. Therefore, a stress-strain curve can be determined from these two signals. The details of the calculations are presented in Gray3.

With respect to the alignment of the bars, the level of signal on the incident bar gage between the time of the end of the incident pulse and the return of the reflected pulse is of interest. If there were no constraint from the bearings, i.e. the bearings perfectly aligned and the bar perfectly straight, then there should be no reflections as a precursor to the
return pulse. Our signal indicates there is probably some reflection from the bearings supporting the bars, but this condition is difficult to quantify and there are possibly other sources of non-zero signal in this time period. Future work will involve purposely misaligning the bearings and comparing the strain gage output signals, thereby determining the magnitude of the effect of a known misalignment.

Conclusions
The construction of the NIST Kolsky bar apparatus is complete, and tests on several materials at room temperature have been completed. Preliminary pulse heating experiments have also been completed. However, tests using the combined system in which samples are pulse-heated prior to compression have not yet been completed. Preliminary results indicate that the bar alignment method was successful, but that there is still some problem with reflections from the bearings. Future work will involve special experiments to quantify the effects of any misalignment.

Disclaimer
Specific manufacturers have been mentioned to aid in the complete documentation of the equipment used for this project. This is not an endorsement or recommendation in any way for a particular manufacturer’s equipment.

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References
4. Gray, ibid, pg. 464