Automation of Mechanical Testing

David T. Heberling
Editor

STP 1208

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ASTM Publication Code Number (PCN)
04-012080-23

ASTM
1916 Race Street
Philadelphia, PA 19103

Library of Congress Cataloging-in-Publication Data

Automation of mechanical testing / David T. Heberling, editor.
(STP 1208)
Contains papers presented at the symposium held in Pittsburgh on 21 May 1992.
"ASTM publication code number (PCN) 04-012080-23."
Includes bibliographical references and index.
ISBN 0-8031-1868-6
1. Testing-machines--Automation--Congresses. I. Heberling, David T. II. Series: ASTM special technical publication ; 1208.
TA413.A88 1993
620'.0044--dc20 93-16119
CIP

Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

Printed in Philadelphia, PA
March 1993

Foreword

This publication, *Automation of Mechanical Testing*, contains papers presented at the symposium of the same name, held in Pittsburgh, PA on 21 May 1992. The symposium was sponsored by ASTM Committee E-28 on Mechanical Testing. David T. Heberling, Armco Steel Co., L.P., Middletown Works Metallurgical Laboratory, Middletown, OH, presided as symposium chairman and is editor of the resulting publication.

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Overview

Because automated mechanical testing is here to stay, ASTM must come to terms with the use of automation and should waste no time addressing standardization issues associated with this technology. This was the thinking of ASTM Committee E-28 when we first decided to hold a symposium on the subject of automated testing. Two years later, the attendance, presentations, and discussions at the resulting symposium confirmed that automation is definitely a topic of interest.

Background

The 1990s can, for our purposes, be considered the second decade of automated mechanical testing. During the 1980s, test machine manufacturers first began to supply significant numbers of tensile test machines equipped with PCs and specialized hardware and software for control of the testing and handling of specimens. By now, it is widely accepted that automated testing has many benefits to offer, and many labs, particularly those running large numbers of similar tests, have implemented automated test systems to reap these benefits.

As often occurs with emerging technologies, there has been an initial flurry of activity, during which it was difficult for standardization efforts to keep up with the fast-breaking developments. Such was the case for standards under the jurisdiction of Committee E-28. Many labs jumped at the first opportunity to cut costs and improve repeatability and reproducibility through automation, even if they had to use nonstandardized procedures to do so. This has complicated the task of standardizing, because no matter what is balloted, there is a good chance that it will contradict a procedure already in use and will therefore draw negative votes.

Hopefully, the initial flurry of activity has now subsided enough that the '90s can be a decade of maturing and standardization of automated test procedures. To help achieve this goal, we present in this STP nine technical papers on the automation of mechanical testing. The first five form a primer for those preparing to implement automated testing. These papers consist of information obtained "the hard way"—from experience with automation projects. Beginning with the fifth, which fits into both categories, the papers focus on specific technical issues and topics, many of which affect or need to be addressed by ASTM standards.

What Do We Mean by Automation?

We begin with a paper from Ruth which discusses what the term "automation" actually means. The author points out that this term has been applied over the years to many hardware advances that have decreased human involvement. (For our purposes, an automated test is loosely defined herein as one that is computer-controlled and that uses specialized hardware and software to ensure that little operator intervention, if any, is required.)

Ruth's paper is a good introduction to the subject in that it discusses the different levels of automation, pointing out the advantages of each. Taking expense and effort into account, the author indicates the approximate testing levels at which the various levels of automation become viable options. He then reviews an aluminum manufacturer's step-by-step automation of a production tensile testing laboratory, offering observations of what made this particular effort a success. Readers who are preparing for (or involved in) such an endeavor are advised to take note.

Additional Considerations

Next is Gebhardt's general discussion of robotic testing. He, like Ruth, has been involved in many automation projects, and his paper resembles Ruth's in that it points out many considerations that have proved to be of great importance. However, Gebhardt's paper focuses on robotic testing as a production system and stresses the importance of project strategies and functional specifications. He also discusses maintenance and support, which definitely need to be kept in mind when purchasing robotic systems. (The more complex a system, the more opportunity there is for something to go wrong; and the more one relies on a single machine for throughput, the more significant any outage of that machine will be!) For examples, Gebhardt refers to an integrated steel mill's automation project.

Several of Gebhardt's attachments will be of particular interest to the reader considering automation. One, for example, shows approximate test times associated with various levels of automation. Another shows the times that various types of robotic systems can be left unattended, and a third shows the corresponding depreciations.

The State of the Art

The third paper, by Mumford, discusses the state of the art, identifying many ways in which the advent of the PC and other developments have greatly changed mechanical testing in the last 20 years.

Topics of this paper include:

- The revolutionizing of test machine design due to PCs
- Enhancements in accuracy of measurements
- Calibration considerations
- Advantages of PC controlling
- Robotic and automated feeding systems
- Standardization of report formats
- Data storage issues
- Use of mathematical models.

This discussion should be useful to the reader who is struggling with the many details associated with automating—whether he is evaluating commercially available systems or developing his own.

A Case Study

Next is the first of two case studies. Carter and Gibbs provide a detailed description of the progress that has been made at Los Alamos National Laboratories.

First, the details of acquiring data from many different types of mechanical tests, some of which are quite complex, are discussed in depth. Then the authors describe the Mechanical Testing Systems Network. This network has become very complex and powerful and currently incorporates over 30 PCs and workstations, a central file server, and a variety of output devices—all linked together via thickwire ethernet and connected to the rest of the world via Internet. Finally, the Los Alamos data analysis software is described by working through an example in which the raw data for a simple tensile test are reduced to provide meaningful results.

This paper shows how far automation has already been taken by those who committed to it early and who have put considerable effort into it. For those who are just now "getting their feet wet," the prospects may be a bit overwhelming, but we can all definitely learn from this experience!

And From the Editor's Experience

We then move to the Heberling paper. This case study gives an end-user's account of the complications and issues that were encountered in the course of purchasing an automated tensile test machine and linking it to a Lab Information Management System.

General topics of the paper include:

- ASTM issues (those related to existing standards)
- Other technical issues and details
- Benefits of semi-automatic testing
- Plans for the future.

Although much general information is provided, the thrust of the paper is to point out many areas in which ASTM can make the task of automation more straightforward—by revising its standards. (Many revisions are, of course, being developed or balloted at this writing.)

While on the Subject of Standardization

The next paper, by Khan, focuses on a point made in the editor's paper: that ASTM standards should define properties in definitive mathematical terms. Khan's paper takes this a step further and suggests the best way to define the properties is to standardize the algorithms used for their determination. (Software used to analyze raw tensile test data, Khan believes, should employ particular logic in doing so.) The paper also presents several algorithms developed by Khan and his company for consideration by the reader and by ASTM.

Unlike most of the papers in this STP, this one includes examples and terminology taken from the mechanical testing of plastics. This should not diminish the usefulness of the paper to those involved in metals testing, for one could easily rework the terminology and details and apply this work to the testing of metals. As such, this paper should be food for thought for all ASTM committees involved in the standardization of mechanical testing.

Elongation at Fracture

The seventh paper, by Scherrer, compares automatically determined elongation at fracture to percent elongation determined by piecing together the broken halves of a tensile specimen and measuring the final distance between gage marks.

The paper reports that the two results agree quite well, that elongation at fracture results are generally the more conservative of the two, and that there seems to be slightly less variation in elongation at fracture results, as compared to a well-controlled procedure for measuring percent elongation. Scherrer also notes that best fit linear regressions can be effectively used to predict percent elongation based on the automatically determined elongation at fracture.

Since manual percent elongation measurement requires operator intervention, fully automated systems have used elongation at fracture for some time now. Only at this writing, after four years of effort, are revisions finally being made to E 8 and E 8M to explicitly permit use of automatically determined elongation at fracture in place of manually measured percent elongation—a bit of convenient timing for this STP!

Determination of Yield Point Elongation

Next is a paper by Young on the calculation of yield point elongation (YPE) by automated test systems. Some fairly complicated mathematics are involved in this because it is very difficult to create software sophisticated enough to detect the slightest hint of YPE *and* to correctly differentiate between YPE and noise. (Although some may not have realized this, the operator has been doing some fairly sophisticated visual analyses all these years in looking for and measuring YPE from *X-Y* recorder charts!)

This paper also touches on a theme that has been mentioned in other papers. Specifically, Young notes that he first had to settle on a definitive mathematical definition of YPE, because such a definition is not provided in ASTM standards today. (Until this is done, a multitude of approaches can be attempted, because the task at hand is not clearly identified.) Clearly, something must be done in this respect. Fortunately, something *is* being done; task group E28.04.10 is currently balloting new definitions for a number of mechanical properties, including YPE.

Bandwidths and Data Rates

We close with a highly technical paper by Nicolson on event criteria for determining bandwidths and data rates to be used in automated tensile testing. This paper shows that, for the measurement of slopes and peak values of waveform events to a given accuracy, the required bandwidth and data rate can be estimated by using convolution of the impulse response with various waveshapes.

This paper should be of much interest to electrical engineers and parties involved in the design of test equipment. Others, such as end-users, may have a difficult time with some of the concepts. Nevertheless, reading through the paper will certainly help the reader gain some understanding of the kinds of technical details that are involved in the automating of mechanical testing, though details such as these are generally dealt with by the test machine manufacturer. Also of use to the end-user is the paper's demonstration that improper selection of bandwidth and data rate can have drastic effects on test results.

The papers outlined herein contain much useful information on the automation of mechanical testing, as provided by experts from test machine manufacturers and R&D facilities and, in the case of the editor's paper, from a previously inexperienced end-user who has become somewhat experienced out of necessity! I gratefully acknowledge the efforts of the authors, reviewers, and ASTM personnel that have made the symposium and this publication possible.

Enjoy!

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Earl A. Ruth[1]

Elements of Automated Mechanical Testing

REFERENCE: Ruth, E. A., **"Elements of Automated Mechanical Testing,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 5–9.

ABSTRACT: For over 100 years, the words "automatic" and "automated" have been used to describe equipment that tests the mechanical properties of materials. This paper attempts to categorize the various levels of automation used in the past, present, and future. It focuses on the building blocks of automation in use, how to decide what level of automation is correct for an application, and how and what is necessary to integrate the entire system into your process.

This work is based on personal experience with several systems installed in different laboratories. The case cited is the automation of tensile tests in a production test laboratory of an aluminum manufacturer; however, much of the information can be universally applied to other types of tests.

This paper is intended as a primer for those interested or involved in increasing the level of automation in their laboratory.

KEYWORDS: automated tensile testing, tensile testing

In the mechanical testing community, the words "automatic" and "automated" have been used almost as long as there have been universal testing machines. Figure 1 is an advertisement for a machine built in 1891. Notice the word "Automatic" in the title. In the years since then, these words have been used and are still in use in many contexts.

The words "automatic" and "automated" were used over the years to describe many advancements. Electronic extensometers that drove load-elongation recorders, testing machines connected to typewriters via solenoids to print out the maximum load, and universal testing machines designed to sequence through a series of functions independent of the operator are just a few examples.

More recently, the words "automatic" and "automated" have been used to describe testing machines that have computerized data acquisition and control systems. For the last five to ten years, these two terms have been used in conjunction with testing systems interfaced to host computers, with specimen handling systems which perform a variety of functions that can operate for hours with minimal operator intervention.

While it would seem like the automatic machines of the distant past have nothing in common with the automatic testing systems of the present, there is a common thread. The purpose of all of these innovations was and is to reduce human involvement, thereby saving time and reducing human bias.

As an example of a building block approach to automation, a production laboratory that performs tensile tests on aluminum in several different specimen configurations will be discussed. While many innovations had been used over the years, we will go back a little over ten years, to a time when all tensile tests were being done on universal testing machines

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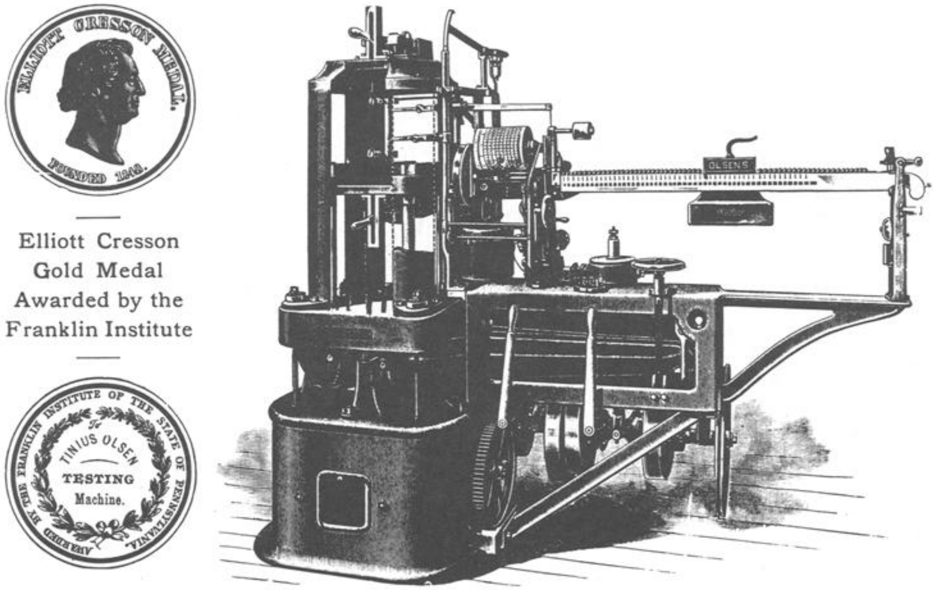
Olsen's New Automatic and Autographic Testing Machine

100,000 and 200,000 lbs. Capacity



Patented June 1, 1880; March 12, 1889; January 27, 1891.

In the above illustration is shown our New Automatic and Autographic Testing Machine. The advantage of the machine making its own record is obvious, especially so for correctly recording the elastic limit or yielding point; also, the advantage of following up the character and amount of yielding that takes place in the specimen corresponding to the applied stresses. We are now prepared to make many different sizes of this machine; all details being worked up to a point giving speedy and satisfactory results with great facility.

For further detailed description of this machine, see pages 64, 68, 69 and 71, as well as adaptation, page 7.

Dimensions, Weight and Prices.

100,000 lbs. Capacity.	Length, 8 ft.	Height, 5 ft. 8 in.	Breadth, 3 ft. 5 in.	Weight, 4,800 lbs.	Price, $
200,000 lbs. "	" 8 ft. 9 in.	" 8 ft. 10 in.	" 4 ft. 5 in.	" 10,400 lbs.	"
300,000 lbs. "	" 11 ft. 4 in.	" 10 ft. 6 in.	" 4 ft. 8 in.	" 20,000 lbs.	"
400,000 lbs. "	" 12 ft.	" 11 ft.	" 5 ft. 4 in.	" 23,000 lbs.	"

FIG. 1—*Advertisement for a Universal Testing Machine designed and built in 1891.*

with extensometers and recorders. The data were reduced manually by the operators and recorded on paper. Several different machines were used to reduce set up time for varying specimen configurations. From the time material to be tested arrived at the lab until the time the product sampled was released for shipment, one to two weeks would pass. As a result, millions of pounds of aluminum were in inventory at all times, creating handling and storage problems, and having a negative financial impact.

A plan was introduced for a robotically loaded tensile testing machine that would be capable of testing 0.252 in. (6.40 mm), 0.357 in. (9.07 mm), and 0.505 in. (12.83 mm) round specimens and flat specimens from 0.005 in. (0.127 mm) to 0.500 in. (12.70 mm) thick. The plan, although not fully implemented at that time for a variety of reasons, did establish a goal.

The first step in realizing this goal was to develop a unified identification scheme. Each specimen had a unique number, which identified not only the coil or plate the specimen was taken from, but the test to be performed and the test direction as well. This identification system was part of a plant-wide tracking system that contained the information on which tests were to be run. The material to be tested was tagged with its ID number on the plant floor. When the specimens were machined for the required tests, they were then tagged with their individual ID numbers. A unique identification scheme is essential.

The second step was to purchase computer-controlled testing machines with data acquisition systems and automatic extensometry. With this equipment, specimen gripping devices close automatically and the extensometer attaches itself to the specimen at the start of a test. The extensometer stays on the specimen until the specimen breaks, in order to record the elongation at fracture. These machines freed the operator, during each test, to prepare for the next test, so 125 to 150 specimens per shift could be tested on each machine. These machines were then interfaced to the plant-wide tracking system so that the results could be made immediately available eliminating the need for manual data entry. This step eliminated data entry errors and sped the release of information to the shipping docks.

The next focus of attention was automation of the specimen measuring process. Laser micrometers for round specimens and electronic gages for flat specimens were interfaced to the data acquisition systems on each of the testing machines. This step reduced data entry errors.

The next step was to further automate the identification system. A laboratory bar code identification and specimen tracking system was installed. Upon entry of the raw material into the laboratory, bar code labels for all of the required test specimens were generated.The bar code system generated these labels based on information received from the plant-wide tracking system. At the same time the labels were generated, a file was opened on a personal-computer-based Local Area Network (LAN). This file contained the tests required for the coil or plate as well as the required minimum/maximum test results. This information was downloaded from the plant-wide tracking system. The test results were maintained in this file until all tests were complete. If all of the results were within specification, the results were uploaded to the plant-wide system. The software on the LAN allowed the laboratory manager to generate reports such as retests required, overdue test results, number of tests per day, etc. The test results remained on the LAN for two weeks, at which time they were archived.

Bar code readers were installed on each of the testing machines and were interfaced to the data acquisition and control system. The data acquisition and control systems were interfaced to the LAN. As the specimens were machined, the bar code labels were affixed. (Note: Bar code labels were not put on round specimens, instead they were placed in numbered racks. The specimens in each rack and their rack locations were maintained in a file on the LAN.) When specimens were tested, the label was scanned by the operator, then (via the LAN) the system obtained the information required to perform the test and placed the results in the appropriate file. This step further reduced operator input errors and automated the procedure of releasing material for shipment.

To further automate the process, force indicating systems that could change force ranges automatically or on demand were required. A system with 0.5% accuracy over a range of forces where the lowest calibrated force is 1/500 of the maximum force, was installed on the testing machine. This permitted a large variety of specimen sizes and strength levels to be tested without adjusting the testing machine.

At this stage, the operator only had to scan the bar code, place the specimen in the specimen measuring device, put the specimen in the testing machine, press a key on the computer to start the test, and when the test was completed, remove the broken specimen halves. The next logical step was to install a specimen handling system that would perform these steps, so that the entire tensile testing system could be left unattended for longer periods of time. A dedicated specimen handling system was installed on a machine to do just that. The system picked a specimen from a magazine, measured the thickness and width, placed it under a bar code scanner, and inserted it in the testing machine. Since the laboratory bar code identification and host interface system was already in place, interfacing the machine to the laboratory was simple and straightforward.

This system tested flat specimens 0.006 in. (0.152 mm) to 0.10 in. (2.54 mm) thick and had a specimen magazine which held up to 150 specimens. It tested 250 to 300 specimens a shift.

With this machine in operation, the next milestone was to automate the testing of flat specimens up to 0.05 in. (12.7 mm) thick. For this application a programmable robot was incorporated to afford more flexibility. (Some of the material to be tested was tread plate which necessitated special handling procedures. Handling this product properly would have been difficult with a dedicated handling system.) This second testing machine was specifically designed to be loaded with a robot. While the robot was a little bit slower than the dedicated handling system used on the first machine, its flexibility and reliability far outweighed the time sacrificed. As a result of the success achieved with the robot on this second machine, the handling system on the first machine was replaced with a robot.

Another system, similar to the second system incorporating the robot, was ordered to test 0.505 in. (12.83 mm) round specimens. This system was installed in August 1992.

Looking back at the goal first established in 1980, everything has been accomplished with the exception of automating the testing of 0.252 in. (6.4 mm) and 0.357 in. (9.07 mm) rounds. An evaluation of the number of these types of specimens being tested has indicated that there is simply not enough volume to justify robotic automated testing of these specimen types.

How the Goal was Realized

(1) A Goal was Established with Realistic Milestones

Establishing a goal required an honest evaluation of the testing requirements. The level of automation which was right for the laboratory was determined (Table 1), based on the number of similar tests. The emphasis was placed on the majority of tests rather than 100% of the tests. The goal was to automate 80% of the tests. Trying to automate 100% of the tests would have made the problem so difficult, complex, and expensive that little would have been accomplished.

TABLE 1—*The level of automation to consider based on the number of similar specimens tested per day.*

Number of Similar Specimens per Day	Level of Automation
1–20	Computer Data Acquisition
10–50	Computer Controlled Testing Machine
50–100	Interface to Host Computer
100–200	Automated Specimen Identification System
100–300	Automated Specimen Loading System

(2) Yearly Re-Evaluation of the Goal and Milestones

Technology is changing rapidly, as are testing requirements. What may have been unrealistic and impractical yesterday is achievable today. As techniques and equipment became available the goal was modified to take advantage of the emerging technologies. As an example, personal computers were in their infancy when the initial goal was established. Now PCs are being used for a variety of tasks throughout the laboratory.

(3) Working on the Milestones

Laboratories are generally set in their ways and reluctant to change their way of doing things. Overcoming this inertia requires a lot of hard work and effort by the equipment supplier and user alike. The easy way out is to do nothing. By chipping away at the milestones one by one, together, the ultimate goal was realized.

Conclusion

Automated testing has been with us for over 100 years. The definition of automated testing has changed and is continuing to change. The correct level of automation to use is dependent on the state of the art and on your testing requirements. The key is to take advantage of the level of technology available that improves your test results and reduces costs.

Peter Gebhardt[1]

Experiences in the Automation of Mechanical Testing

REFERENCE: Gebhardt, P., **"Experiences in the Automation of Mechanical Testing,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 10–18.

ABSTRACT: To be competitive, mechanical testing has to be automated to a high degree, up to ghost shift if possible. To effectively automate the laboratory, certain rules have to be followed. Mechanical testing systems are no longer laboratory machines, but have to be thought of as production systems. The new European Standard, EN 10002, is taking computerized automated testing into consideration.

Automation has to fit into the strategic objective of the company. This means that management has to promote the project.

As not only testing is concerned, a group of experts have to cooperate. The following disciplines are involved and have to be coordinated: Testing, Specimen Preparation, Process Control, Laboratory Data Management, Maintenance, Employees, and Safety. An example is shown in Mechanical Testing and Laboratory Automation in an Integrated Steel Mill.

KEYWORDS: automated tensile testing, specimen preparation, specimen identification, maintenance guarantee, skill of personnel

Remaining or becoming competitive in quality and price is the goal in testing. Approaching this goal is a must for any industry. In production, robot systems have been used for a long time (Fig. 1). For testing metals, the first robot systems have been in use in Europe since 1986. For these types of tests (Fig. 2), you can consider a production machine as a testing system.

The number of repetitive tests to be performed is the primary criterion when evaluating an automated testing system. Other criteria for this decision include:

- transport of samples or raw material
- specimen preparation
- incorporation into an existing data communication system
- availability of skilled personnel
- required time to have results available.

The conclusions reached from such an analysis may justify a fully automated system, data acquisition only, or having the tests performed by a subcontractor off-site, or a combination thereof.

Figure 3 shows the test times for one person using different degrees of automation. As shown in Fig. 4, different degrees of automation are available and should be selected depending on the number of tests involved. Of course, economic issues and the justification for the investment in an automated test system will be the main criterion (Fig. 5).

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[1] Managing director, Roell + Korthaus/MFL, Haan, Germany.

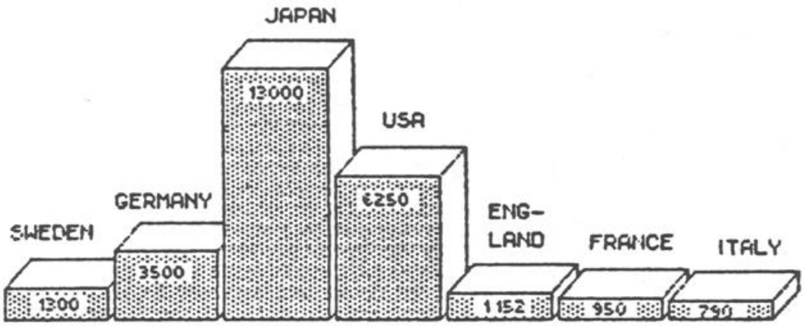

FIG. 1—*Use of industrial robots, 1987–1988.*

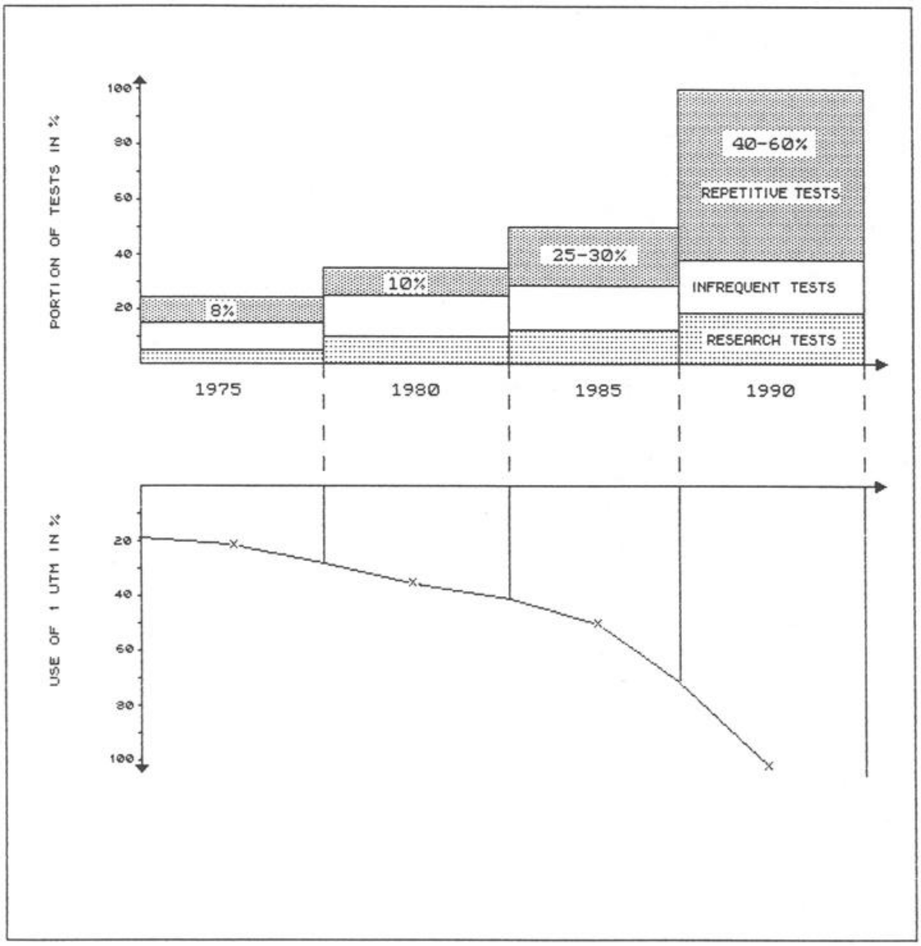

FIG. 2—*Portion of tests in percent.*

	TYPE OF LOADING	SPECIMENS IN ADVANCE	TIME, SYSTEM CAN OPERATE UNATTENDED
HANDLING A	AUTOMATIC TENSILE SPECIMEN LOADING	5 SPECIMENS	10 - 20 MIN (COVER COFFEE BRAKE)
HANDLING A	AUTOMATIC LOADING WITH LARGER MAGAZINES	15 SPECIMENS	30 - 60 MIN (COVER LUNCH HOUR)
HANDLING A / HANDLING B	PLUS AUTOMATIC SPECIMEN MEASUREMENT	50 SPECIMENS	100 - 200 MIN (EXTENDED THE WORK SHIFT)
HANDLING B	PLUS INCORPORATION OF ADDITIONAL TESTING UNITS SUCH AS HARDNESS AND SURFACE ROUGHNESS TESTING	200-400 SPECIMENS	400 - 600 MIN (UNATTENDED WORK SHIFT - GHOST SHIFT)

FIG. 3—*Different degrees of automation.*

Common basic objectives of an automated system are:

- immediate availability of data
- traceability of data
- minimization of operator influences
- data management
- flexibility.

Figure 6 shows the organization of the physical testing facility in an integrated steel mill. The task was to integrate robotized test systems into this environment. The following shows how this target was actually obtained.

Application

Requirements of Customer

These included:

(a) results available within eight hours after arrival of the material to be tested
(b) tests to be completed with 1.5 operators in an eight-hour shift
(c) specimens inserted into the tensile machine with an angular accuracy of 5 min
(d) accuracy of extensometer better than 0.25 μm for the whole range.

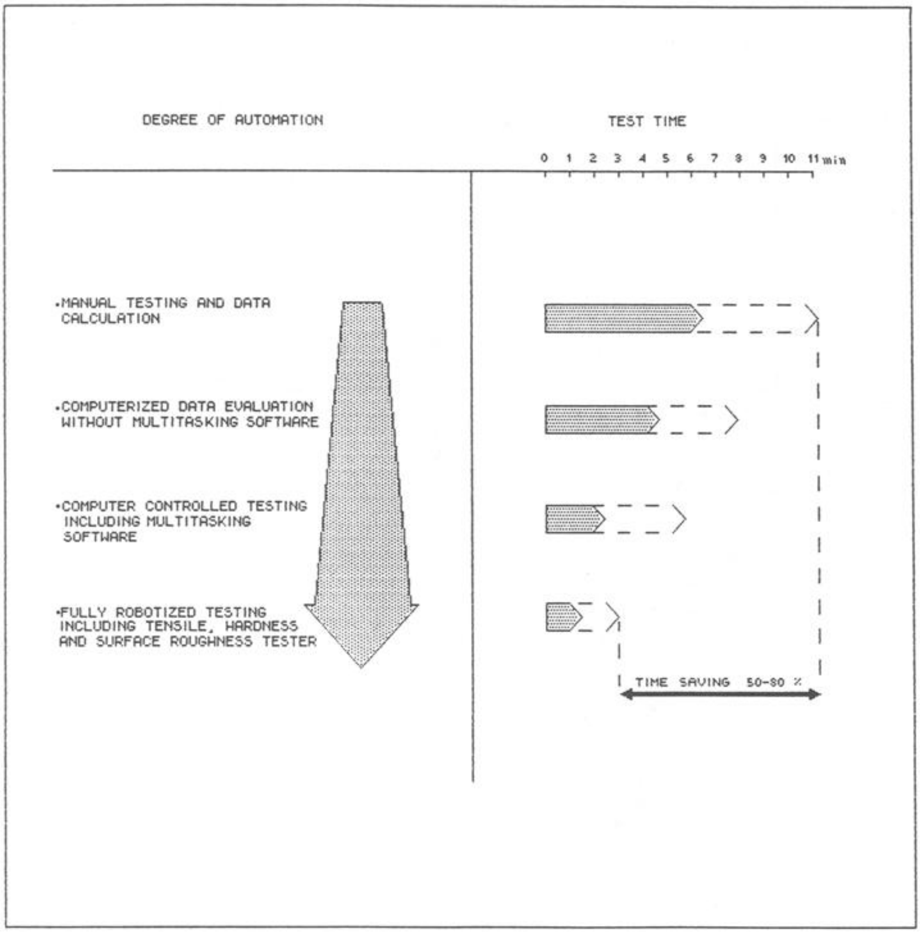

FIG. 4—*Time-saving by automation.*

Material:	cold-rolled steel
Thickness:	0.2–3 mm
No. of tests per day:	400
Standards:	EN 10002, ASTM E 8*

Results were obtained for: Thickness, Width, Cross-sectional area, Gage length, Upper Yield Point, Lower Yield Point, 0.20% Offset Yield Strength, 1.0% Offset Yield Strength, Yield Point Elongation, Yield Point Elongation Type, Uniform Elongation, Total Elongation, *r* value, *n* value, HR 30T, HR 40T, and Surface Roughness average height of peaks and average number of peaks.

Material:	hot-rolled sheet steel
Thickness:	3–16 mm
No. of tests per day:	200
Standards:	EN 10002, ASTM E 8

* Test Methods of Tension Testing of Metallic Materials.

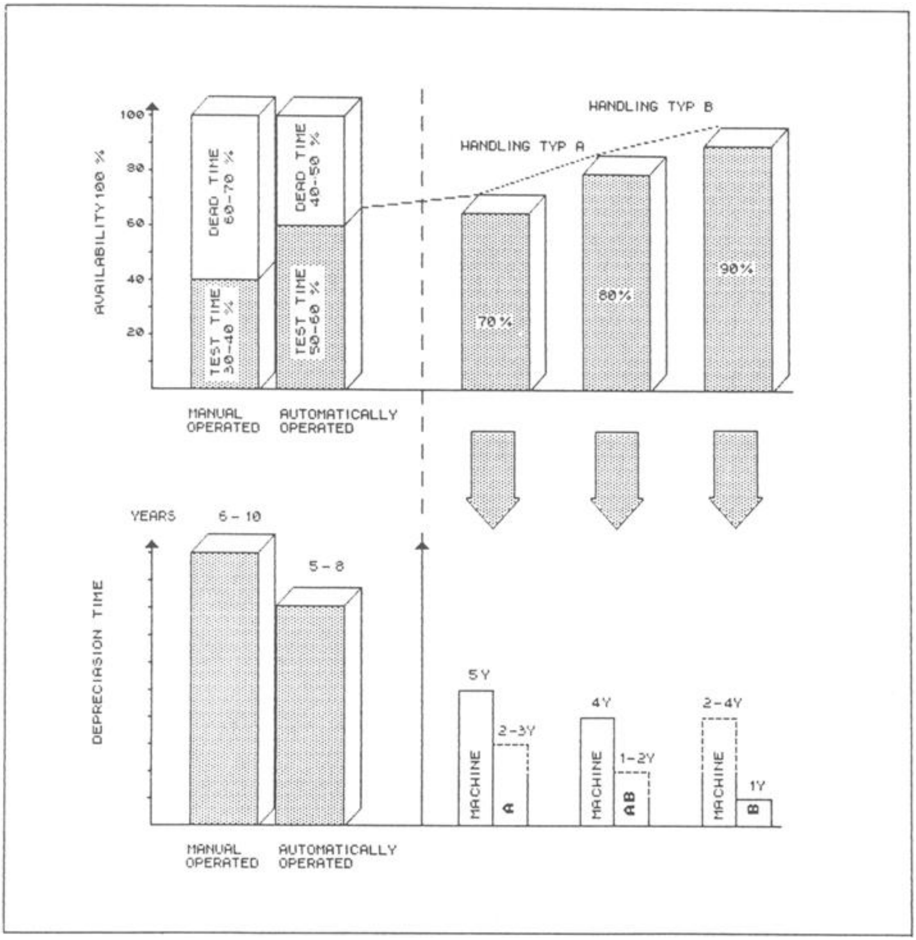

FIG. 5—*Economic considerations for the use of robotized test systems.*

Results were obtained for: Thickness, Width, Cross-sectional area, Gage length, Upper Yield Point, Lower Yield Point, 0.20% Offset Yield Strength, 1.0% Offset Yield Strength, 0.5% Elongation Under Load Yield Strength, Yield Point Elongation, Yield Point Elongation Type, Uniform Elongation, and Total Elongation.

Material:	hot-rolled steel plate
Thickness:	4–60 mm
No. of tests per day:	120
Standards:	EN 10002, ASTM E 8

Results were obtained for: Thickness, Width, Cross-sectional area, Gage length, Upper Yield Point, Lower Yield Point, 0.20% Offset Yield Strength, 1.0% Offset Yield Strength, 0.5% Elongation Under Load Yield Strength, Yield Point Elongation, Yield Point Elongation Type, Uniform Elongation, and Total Elongation.

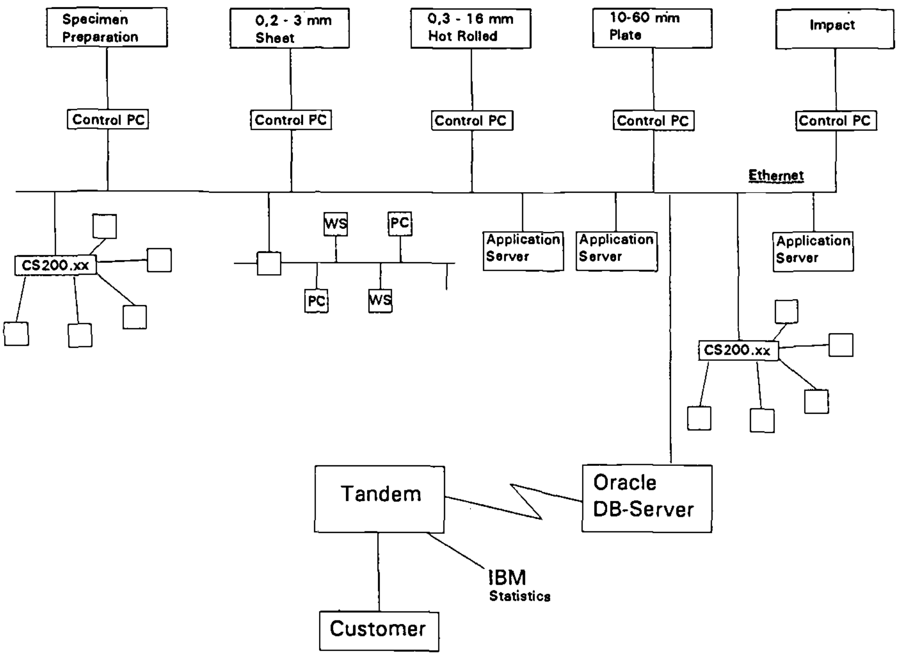

FIG. 6—*Data communication structure.*

Questions Asked by the Equipment Supplier

These included:

(a) dimensional tolerances of the specimen geometry
(b) specimen identification system
(c) personnel skills
(d) maintenance support
(e) work rules/restrictions
(f) safety and environmental requirements
(g) responsibilities of The Project Manager.

Functional Analysis Document

The requirements of the customer and the answers to the questions asked by the supplier should be incorporated into a functional analysis document covering all issues (Fig. 7). During the discussions the following additional solutions had been agreed upon:

(a) specimen ID by bar code
(b) ability to introduce all data manually
(c) guided transport of specimen to guarantee axial alignment accuracy
(d) use of SPC specimens in the beginning and in the middle of each shift to check the performance of each unit

Functional Analysis (Index)

1. Requirements
   - 1.1. specimen drawings
   - 1.2. installation drawings

2. Hardware description
   - 2.1. loading unit
   - 2.2. hydraulic parallel grips
   - 2.3. automatic extensometer
   - 2.4. hardness tester
   - 2.5. surface roughness tester
   - 2.6. specimen measuring unit
   - 2.7. specimen magazine
   - 2.8. handling system
   - 2.9. PLC
   - 2.10. computer equipment
   - 2.11. spare parts

3. Software
   - 3.1. test software
   - 3.2. screens
   - 3.3. host mode
   - 3.4. stand alone mode
   - 3.5. print out formats
   - 3.6. special functions

4. Installation Requirements

5. Delivery, Erection, Start-Up
   - 5.1. PAT Pre acceptance testing
   - 5.2. training
   - 5.3. FAT On site acceptance testing
   - 5.4. documentation

6. Time Schedule

FIG. 7—*Functional analysis document.*

(e) comparison between nominal values (upper/lower limits) stored in a host computer with the following actions:
   (1) if the bar code is unknown/unreadable—no testing
   (2) if the thickness varies by more than $x\%$—no testing
   (3) if the thickness is out of tolerance, 3 times in a row, stop testing and give an acoustic/optical signal
   (4) if one of the test results is out of tolerance, place the broken specimen in a separate bin and print the stress/strain curve
   (5) if a given test result is out of tolerance, 3 times in a row, stop the specific unit involved and give an acoustic/optical signal

(f) transfer of the stress/strain data pairs to a host computer

(g) create a time schedule including project meetings to check design, parts ordering, assembly, and software testing, and
(h) develop a strategy for operator/maintenance training.

Acceptance Criteria/Guarantees

The factory and the final acceptance test were based on the detailed specification of the functional analysis. The better prepared this functional analysis is, the less complicated and faster the acceptance tests will be.

Major issues for a robotized test system, since it is considered a production machine, are service, maintenance, and as a result the guaranteed availability of the system.

Three types of service/maintenance strategies can be considered and again have to fit into the global strategy of a company:

Global service/maintenance from the supplier—This is chosen if a company has decided to decrease the fixed cost/personnel and to exchange these fixed costs into variables, i.e., product related cost. This means no on-site maintenance is available and everything is

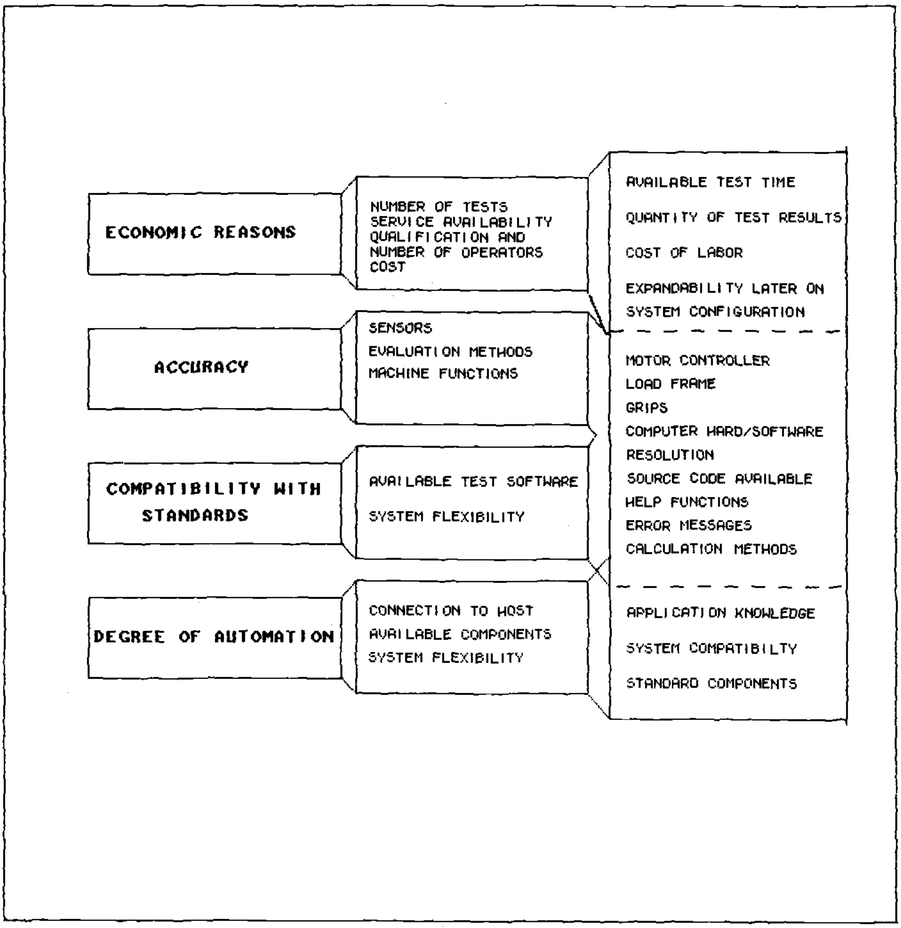

FIG. 8—*Criteria for selection of a system.*

purchased and provided by subcontractors. The supplier can provide two types of service contracts:

(a) fixed price per year including all costs (parts and labor),
(b) visits on request, parts to be invoiced separately, customer has no available spare parts on-site.

Maintain in-house service/maintenance capabilities—This is done to a certain extent, and a small stock of spare parts for quick actions is maintained.

Maintain in-house complete service/maintenance capability—This will include a large stock of spare parts to be completely independent from the supplier, and also an availability of source codes for software.

The decision of which way to go depends on the skills of the available personnel and the response time of the supplier. In any case, *regular preventative maintenance is absolutely necessary*. During this preventive maintenance, parts to be changed during the next visit can be defined and ordered. For solutions 2 or 3, documentation and training play a key role. After putting all of these factors together, the net resulting objective is to have at least a 96% availability of the complete system and a 36-hour service response including weekends.

How to Decide/Checklist for Decision

All mentioned points lead to a matrix, which may be entirely different from case to case (Fig. 8) and helps to promote an automation project in your company.

Conclusion

Market forces and manufacturing economics have clearly demonstrated a need for test laboratory automation in varying degrees. New European standards are taking these new developments into account. Any company exporting to this market will have to comply with these new standards.

ASTM will have to grow with the requirements of automated testing as well. The more sophisticated and flexible the test equipment is, the easier the adaption to new requirements of revised standards can be effected.

Paul M. Mumford[1]

Measurement, Control, and Data Processing Techniques in the Automation of Mechanical Testing

REFERENCE: Mumford, P. M., **"Measurement, Control, and Data Processing Techniques in the Automation of Mechanical Testing,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 19–27.

ABSTRACT: Automation of mechanical testing began about 20 years ago with the addition of computers to provide automatic data acquisition and reduction for tensile tests. This paper will review developments in automated testing, with attention to some particular areas of interest or concern.

The computer, as a testing system component, offers great utility in automation of the testing process. Not only does the computer handle data acquisition and reduction, but also performs data storage and testing machine control functions.

The interface devices that allow the computer to access force and extension measurements and to control the loading process have improved many fold, and some new measurement devices, such as electronic calipers and optical extensometers, have been introduced.

Much progress has been made in algorithms and mathematical models for analysis of the data collected during the test. Particular attention will be given to modeling the data storage.

KEYWORDS: automation, calibration, computer, control, measurement, laser, extensometer

Testing System Design

Testing machines are now designed with computers in mind. Many of the features expected to be found in a new testing machine today need a computer as the most practical and economical means of execution. Those features include:

- Automatic ranging
- Overload protection
- Selection of a variety of measurement units
- Temporary storage of the test curve to allow replotting or operator interaction after the test is over
- Reliable automatic specimen break detection
- Automatic stop or return functions
- Preset and continuously variable test speeds
- Load or strain control in addition to crosshead position control
- Cyclic testing
- The ability to accept programs for automation of testing without additional equipment
- Data storage in computer compatible form
- Facilities for attachment of enhancements such as linear measuring tools, data networks, barcode readers, etc.

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A fully integrated system is designed with one or more computers included from the beginning. The computer not only provides capability for the desirable features previously noted, but also the control logic for operation of the testing machine loadframe and automation hardware. A separate "Manual Control Panel" is no longer required. Using the computer keyboard for manual control substantially reduces the cost of the system.

Measurement and Calibration

Recent developments in electronics have made vast improvements possible in the measurement and digitization of the force and extension data needed for computer determination of mechanical properties. Present technology provides strain gage amplifiers and analog to digital converters which may be autocalibrated under program control, and are also very stable and accurate. It should be noted that "autocalibration" of the readout devices is similar to "electronic calibration" (shunt resistor calibration). Neither function is a calibration of the loadcell, but rather a single point check of the readout.

The ASTM standards that apply to load verification of testing machines (ASTM E 4), verification and calibration of extensometers (ASTM E 83) and calibration of force measuring instruments for verifying the load indication of testing machines (ASTM E 74) do not contain a definition of "calibration."

According to MIL-STD-45662A Paragraph 3.1, the definition of calibration is: "The comparison of M&TE or measurement standard of unknown accuracy to a measurement standard of known accuracy in order to detect, correlate, report, or eliminate by adjustment any variation in the accuracy of the instrument being compared."

With a traceable transfer standard for force or linear measurement which can communicate with the test system computer, it is possible to automate the calibration of force and strain transducers in a manner that fully meets the objective of a system with known accuracy, traceable to the U.S. standards.

Automation of the calibration process provides several benefits:

(1) More comprehensive calibrations, with more runs and more data points compared.
(2) Operator adjustment of calibration controls is eliminated, reducing the chance of erroneous data due to operator error.
(3) The calibration procedure can be thoroughly developed and programmed to reduce procedural and clerical errors.
(4) Immediate printing of certification documents.
(5) The bottom line is reduced verification time and cost with enhanced system accuracy.

The stability and accuracy of state of the art measuring systems extends the necessary calibration cycle. The need to rely on daily "electronic calibration" or single point "hang a weight" tests for calibration adjustments had disappeared along with the vacuum tube.

In the United States, testing systems must be calibrated periodically with standards traceable to the National Institute of Standards and Technology (NIST) to ensure that they conform to U.S. standards. The day-to-day confidence check of testing machines ought to be done with SPC techniques, using control specimens. This method checks the whole testing process and provides a continuing record of system performance.

Dimensional measurement of the test specimens has also improved with computer application. Electronic linear measuring tools such as calipers and micrometers are now routinely interfaced to mechanical testing systems. They provide measurement accuracy equal to or better than mechanical devices, save time, and eliminate clerical and reading errors.

Other new measurement devices are becoming available. Optical and laser based extensometers are of particular interest, offering the following features and advantages:

(1) The noncontact feature permits measurements to specimen failure without risk of damage to the instrument.
(2) Operating through a window into an environmental chamber allows testing in hostile environments without risk of damage to the instrument.
(3) There is minimal disturbance of the specimen, consisting of very light markings or reflectors, or in some cases no marks at all. Note that instruments which use no marks may not actually measure "extension" defined as "the change in length between fixed points on the specimen" (gage marks), but rather the motion of the surface of the specimen past a pair of fixed points.
(4) Some instruments operate over a very wide dynamic range and with good precision. At least one device can meet class B2 of ASTM Method of Verification and Classification of Extensometers (E 83) with resolution better than 10 microstrain and a range in excess of 100% extension. This instrument can also operate with a range of more than 1000% extension while meeting ASTM E 83 class C.

Controls

Electronic control systems have progressed along with instrumentation. Speed and position may now be controlled using digital measurement techniques and digital computation of the servo equations. This can yield a very wide speed control range and precise control of speed and position of the loading machine.

Integrated computer control of the testing machine offers many advantages:

(1) Flexibility. Control schemes can be revised by programming, requiring no hardware additions or changes.
(2) Cost savings. Using the computer keyboard for manual control has helped to hold system prices down. In 1981, a particular 100-kN testing machine with computer data acquisition and servo control sold for about $38 000. In 1992, its successor (with many improvements) costs $36 750.
(3) Compatibility. Data can be easily moved to other computers for storage or further analysis.
(4) Maintainability. Personal computer (PC) systems are widely used and standardized. Parts and expertise are available everywhere.
(5) Calibration fidelity. Automatic control of ranging and units conversion using digital computing eliminates many of the adjustments needed to calibrate noncomputerized systems. The fewer adjustments, the less the chance of error or tampering.
(6) Automation. The computer is available, and interfaced to allow automation of testing, data analysis, and calibration. No added hardware is required.

Fully Automated Systems

Robot fed and automatically fed testing systems are proliferating, with a promise of great labor savings and more uniform testing procedures.

The robot fed systems allow flexibility to perform different tests on various specimens by reprogramming the robot, but trade off speed and reliability in specimen manipulation.

The automatically fed machines are designed for a particular specimen configuration. They may accommodate some variation in specimens by interchangeable grips, specimen magazines, etc. This generally makes them less flexible than the robot-operated machine. Their advantage lies in the speed and reliability with which they can handle test specimens.

Many automated systems are using barcode labels to identify test specimens. This provides positive identification of each specimen by the automated testing machine. The machine need not depend on the specimens being kept in strict sequence. Using the barcode identification, the machine can file the test results in the proper place even if test specimens are tested out of sequence.

The barcode label is limited to perhaps five to twenty characters, depending upon the physical size available. This may prevent direct barcoding of the complete material identification, but if the barcode identification number is networked with a computer-based test identification system such as Laboratory Information Management System (LIMS) or Management Information System (MIS), then the necessary specification information and material description may be downloaded from the management system rather than being entered by the operator. This arrangement requires a communications link between the management system and the testing machine, but can save a great deal of time and data entry errors. Another benefit of the network is that test results may be fed to the network database, saving time required to transmit written reports.

One automatically fed system tests molded plastic specimens over the temperature range of -40 to 250° C. This system adjusts test temperature and test speed as necessary for each specimen, based on barcode identification of each.

The system also allows the operator to specify a preconditioning time for all specimens tested at other than room temperature. Up to 20 specimens may be loaded into the preconditioning rack for preconditioning to temperature. The system takes into account the expected pull time and the desired preconditioning time in deciding how many specimens to load into the preconditioning rack in advance of testing.

Of course specimens must be sorted into groups by temperature to keep chamber heating and cooling cycles to a minimum.

An "Audit Trail" of test data is printed, one line for each specimen, as they are actually pulled. This provides a permanent record in the event of disk storage malfunction. After a "Magazine" of specimens has been tested, the operator may select the "Report" function to generate printed test reports. The computer is able to organize the test reports into proper sets by reference to the barcode identification, regardless of the actual sequence of testing.

Data Processing

Despite the improvements in controlling the test and acquiring the raw force and deformation data, we ought to keep in mind that measurements are usually inexact values. The portion of measurement errors that are random in nature may be reduced effectively by taking extra readings (over sampling) and then averaging (integrating) multiple readings. This approach is a simple example of digital filtering, and is an effective variance reduction technique.

The filtering process can be optimized if we have some mathematical model or models available that fit the physical process. A good example of this application comes to mind:

The second order polynomial curve fit has been applied to the calibration of elastic force measuring devices (see ASTM E 74, Practice for Calibration of Force Measuring Instruments for Verifying the Load Indication of Testing Machines) for many years. It is so widely used because it so well fits the physical nonlinearity caused by deformation of the elastic device in use.

Carbon fiber poses a similar nonlinearity in that the modulus (stiffness of the material) increases with stress. Carbon fiber has no "straight line" portion in the stress-strain curve.

Data show that the stress-strain curve of a carbon fiber specimen may be precisely described by a second order polynomial.

The polynomial regression curve fitting process is well-known and easily built into computer programs. One of the outputs of the polynomial fit process is an estimate of the standard deviation of the raw input data. Provided that the polynomial does fit the curve, the standard deviation is a useful estimate of the random errors in our measurements. If we now use the polynomial obtained to compute modulus of elasticity at strain levels of interest, we will have minimized the effect of random errors on the modulus values by having integrated the whole data set into the polynomial that describes the natural shape of the curve.

This example is probably the simplest case of a mathematical model that really fits the data. Other cases will require different, and probably more complicated, models. Materials that exhibit discontinuous yielding probably cannot be precisely modeled except in an averaging sense.

Think of an experienced person looking at the stress-strain diagram from a familiar test. That person most likely knows at a glance if the test is atypical. Mathematical models can simulate a mental standard for what the stress-strain diagram should look like, and allow the computer to flag data that is suspect. Given a good model, the computer can be very effective in verifying the quality of the data obtained from a test.

Mathematical models are also a key to algorithms for finding points on the curve that are significant to data reduction, including:

- The "best straight line" part of the curve
- Yield point
- Yield point elongation
- Maximum force point
- Rupture point.

More complex curves will surely require more complex models. For example, curves with inflection points may require multiple models to deal with various segments (parts) of the curve.

Development and standardization of models and algorithms will require a great deal of work and cooperation among the interested parties, but will provide large benefits in return.

Reporting

In general, the report generated for a test should include full details of these areas:

(1) Test equipment used.
(2) Procedure used, including traceability of the algorithms used for data analysis.
(3) Any environmental conditions relevant to the test.
(4) Material tested.
(5) Results obtained.

In addition, where multiple specimens are tested, a statistical summary of the results should be included. The statistical summary provides average values for SPC control charts, along with standard deviation values which are indicators of the quality of the test results.

Considerable progress has been made in standardization of data reporting for some computerized mechanical testing operations. Standardized reporting formats will make data exchange much easier in the future. The accumulation of data from diverse sources in a consistent format will facilitate data base management studies comparing those data.

Raw Data Storage

There are some important questions concerning the storage of test results, particularly the "raw data" stress-strain diagram, that need to be addressed.

We have the raw data set in computer memory at the end of each test. Should it be stored? If so, how? Options include the following:

(1) Discard the raw data after analysis.
    If there is any possibility of future critical review of the data, such as a product liability lawsuit, then the raw data must be preserved to support the analysis.
(2) Store the entire data set.
    (a) Presents no problem for the programmer
    (b) Reproduces the original curve exactly
    (c) Uses large amounts of storage space
    (d) Because of (c) it slows down any search of the data.
(3) Store a limited number of points to represent the whole curve.
    (a) This is a trade-off between the fidelity of the data and the storage space requirement.
    (b) If a suitable model is not available, then this is the only viable alternative to reduce the storage space needed.
    (c) Good data fidelity is possible with a very significant reduction in storage space. Further discussion of an algorithm and an example of its use will follow.
(4) Store a mathematical model of the data.
    (a) Fidelity of the curve is as good as the model.
    (b) This option provides the greatest reduction in storage space required.

Implementation of Option 3 requires an algorithm for deciding which members of the dataset are to be preserved, and an evaluation of the fidelity of the resulting subset.

A simple algorithm (biaxial edit algorithm) has been developed and used to edit a sample curve. This algorithm computes initial sampling intervals for force and strain by dividing the force and extension range values (maximum value minus minimum value) by the constant 200. If the dataset contains less than 255 data pairs then there is no need to edit. The process starts by accepting the first pair; it then scans the original dataset, accepting a point where either force or extension has changed (either increasing or decreasing) from the last-accepted point by an amount greater than the respective sampling intervals computed at the start. The point where force is at the maximum for the curve is also accepted, regardless of change from the previously accepted point, to ensure that the tensile strength value will not be altered.

After the first pass through the process, the number of pairs saved is tested. If it is between 230 and 254, then the process is complete, otherwise another pass is required. The limit of 254 points is arbitrary; more points could be saved if needed.

If the process is complete, then the last point accepted is checked; if it is not the same as the last point of the original dataset, then that last point is also accepted. This avoids losing data from the end of the curve due to the edit process.

If more than 254 pairs were accepted, then the sampling intervals are adjusted by the ratio of the number of points accepted to 230; this makes the sampling intervals larger so that on the next pass, fewer pairs will be accepted.

If less than 230 pairs are accepted, then the sampling intervals are adjusted by the ratio of the number of pairs accepted to 250, making the sampling interval smaller so that more pairs will be accepted on the next pass.

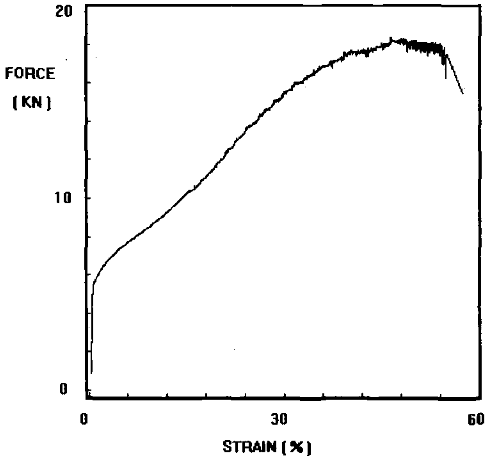

FIG. 1—*Original curve complete.*

The described edit process takes less time than saving the excess data to a floppy disk, so there is no adverse impact on system speed.

The edit criteria are easily changed so that the process can be adapted to accept a number of data pairs appropriate to the test data and the requirements of the user.

This editing process allows the testing system to record as many data pairs as possible during the test, without burdening the data analysis and storage functions with a large number of redundant data pairs. The biaxial editing algorithm ensures that the data pairs accepted are uniformly distributed along the length of the curve and that the number of data pairs is reasonably consistent from test to test.

This approach does, however, lose some fine detail. Computer reanalysis of the data using the edited curve will probably show some small differences from the original results. Graphical analysis will not be affected by the edit.

Computer analysis of the dataset before and after the edit would easily quantify those differences.

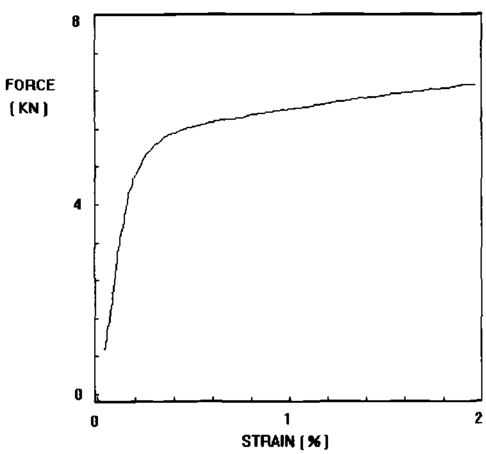

FIG. 2—*Original curve expanded.*

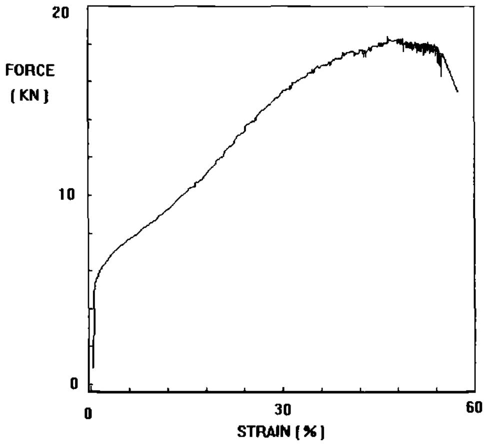

FIG. 3—*Edited curve complete.*

Figure 1 shows the force versus strain curve for a tensile test of 301 stainless steel. The test was run using a Laser Extensometer and force and strain were measured to the point of fracture. This example is a complex curve because it contains much short-term load variation due to work-hardening of the specimen. The original curve contains about 2300 force-strain pairs.

Figure 2 shows the initial portion of the curve expanded to show only the first 2.0% of extension.

Figure 3 shows the curve of Fig. 1 after editing by the aforementioned algorithm. The edited dataset contains 249 force-strain pairs.

Figure 4 shows the edited curve expanded to show only the first 2.0% of extension.

Option 4, the mathematical model technique, can be very precise, provided that the model does in fact fit the curve. The simple case for carbon fiber offers exact replication of the results computed from the polynomial. The curve will be reproduced less any random errors averaged out by the curve fitting process. The fidelity of the reproduced curve can be

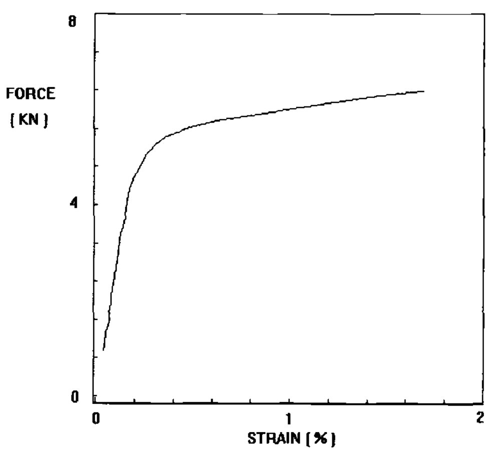

FIG. 4—*Edited curve expanded.*

accurately defined by saving the standard deviation value from the original polynomial regression.

If the original raw data set contains 1000 data points, then:

Option 2 requires storage of 2000 numeric values (1000 for force and 1000 for strain).

Option 3 can reduce this by perhaps 80 to 90%, depending upon the complexity of the curve.

Option 4 (at least in the simple case cited) requires storage of only four values, including the standard deviation estimate. The space advantage of Option 4 would be less with more complicated models.

Summary

A review of the main points:

(1) The computer has made possible a revolution in the design of testing systems.
(2) Measurement accuracy has been enhanced by developments in electronic signal processing and analog to digital conversion. Some new measurement devices and techniques may make data acquisition faster, more accurate, and less expensive. The meaning of "calibration" should be kept in mind, particularly the difference between a system verification and a quick check of the readout system.
(3) Control systems making use of an integral PC offer substantial cost savings, and high performance too.
(4) An integrated computer provides logic and communications abilities to control an automated specimen feed system or to supervise a robot performing the specimen feed operation. The robot is more flexible, but the automated feed system is probably faster and more reliable.
(5) Mathematical models that precisely characterize the stress-strain diagram are the most important aid to data analysis. A good model for a particular material and test should allow the computer to make a very good estimate of the quality of the data and thus the validity of the test. Development of models is a large task. Cooperation among interested parties will speed progress and perhaps result in some standards that would be very helpful to workers in the industry.
(6) Reporting is mentioned because of the work in progress on standardization of data reporting formats. We should be looking also to standardization of raw data storage.
(7) Raw data storage presently ranges from none to overkill. Some laboratories do not even save the curve, or save only a paper copy that cannot easily be put back into the computer for further analysis. Others save multi-thousands of data points, creating a very large database that uses lots of storage space and is slow to search. With good models this problem can be fully overcome. Even a sensible editing algorithm is useful in reducing the volume of raw data to a manageable size.

David H. Carter[1] *and W. Scott Gibbs*[1]

Automated Data Acquisition and Analysis in a Mechanical Test Lab

REFERENCE: Carter, D. H. and Gibbs, W. S., **"Automated Data Acquisition and Analysis in a Mechanical Test Lab,"** *Automation of Mechanical Testing, ASTM STP 1208,* David T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 28–39.

ABSTRACT: Computers and enhanced control technology have made it possible to perform more sophisticated mechanical tests than ever before, as well as to allow routine tests to be run and analyzed with much greater efficiency. Automated data acquisition, storage, and analysis have become key ingredients in a mechanical test facility, especially in one which uses a wide variety of test equipment and techniques. This paper will discuss one such mechanical test facility where many different types of mechanical tests are performed using automated data acquisition, centralized data storage, and finally a complex system of automated data analysis. Various systems of data acquisition will be discussed, including those used on servo-hydraulic and screw-driven systems, as well as those used for higher-rate, formability, and creep tests. Methods for networking equipment used in such a facility will be described. Networking is an important criterion for establishing a centralized data base, and for eventually building a system of automated data analysis.

KEYWORDS: automated data acquisition, data storage, data analysis, networking

Automated data acquisition, networking, and analysis systems have become key features of a successful and efficient mechanical testing facility. There are many items that must be carefully considered before designing such a laboratory, in order to best take advantage of the available technology in these three areas.

This paper will describe one such facility at the Los Alamos National Laboratory in which the automation of data acquisition, networking, and analysis were planned as integral parts of the laboratory during its construction. Many of the procedures and equipment used in this facility could also be used to upgrade existing mechanical test labs.

The first section of this paper will describe various pieces of equipment in this lab, and, in particular, the data acquisition system related to each machine. In the next section, the concept of networking, as it was applied to a mechanical test lab, will be described. Finally, the data analysis system will be outlined.

Automated Data Acquisition Systems

The charter of this mechanical test lab is to provide the highest possible quality mechanical characterization facilities for advanced materials development programs within the Los Alamos National Laboratory. Some of the advanced materials studied in these programs may require characterization at extreme environmental conditions, such as elevated and cryogenic temperatures.

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This work was performed under the auspices of the United States Department of Energy under contract W-7405-ENG-36.

Mechanical characterization services are provided for a wide variety of metals, ceramics, plastics, and composites at temperatures ranging from 4 to 3273 K. Typical strain rates vary from 10^{-8} per second to 5 per second. These operations include, but are not limited to, tensile, compression, bend, impact, and fracture toughness testing. Tests are performed over a wide range of environmental conditions that include gaseous atmospheres, vacuum, acidic and basic liquids as well as metal salts and liquid metals. Some test methods are performed to applicable ASTM standards. Other material characterization requirements may dictate that nonstandard test methods must be employed.

Some of the pieces of test equipment used are: servo-hydraulic load frames; screw-driven load frames; a system used for the simulation of various thermomechanical metallurgical processes; a unique servo-hydraulic metal forming system; creep testing machines (both constant stress and constant load); an impression creep test system, designed and built in-house; a Charpy impact tester; a drop tower; and a fracture toughness tester.

Key features that make a data acquisition system successful in a large networked environment such as this are:

- high accuracy and reliability
- high-speed data acquisition
- use of a standard format for data to facilitate networking and efficient analysis
- data provided in a convenient form for use by the researcher to perform additional specialized analysis
- direct digital data input for numerical modeling of materials and structures.

For the test equipment in this lab, each of these features has been addressed.

Servo-Hydraulic Load Frames

The servo-hydraulic load frames have been equipped to provide the greatest overall capabilities in terms of their load capacities, range of possible strain rates, and environmental test conditions. Some materials commonly tested are U-W, Be, and W-Ni-Fe. Tensile, compression, fracture mechanics, fatigue, and flexure tests are performed on these systems with applied loads ranging from a few pounds to 600 kips (2.67 mN). Temperature capabilities include cryogenic testing down to 4 K and elevated temperature tests up to 2000 K, using both resistance and inductive type furnaces. Other environmental conditions used on these frames include high-vacuum, gaseous atmospheres, acidic or basic liquids, metal salts, and liquid metals.

There are a number of data acquisition systems associated with the servo-hydraulic load frames, depending on the controller being used and the type of test being performed. Some of the specialized test software used in controlling tests is supplied by the manufacturer of the controller. For most tests, however, a sophisticated function generator is used to perform the test.

As an example, test system control and data acquisition on one machine is performed by a DEC Micro-PDP 11/23, interfaced to an MTS 448 series controller and function generator. Up to eight channels of strain gages may be recorded using the instrumentation attached to this load frame.

Another load frame is controlled by a personal computer interfaced to an MTS 458 series controller and micro-profiler. Through the personal computers, the micro-profiler can easily be programmed to generate many different types of test "profiles" for use with the controller.

Raw data from the tests are normally acquired by software written in-house. By writing our own data acquisition software for each piece of equipment, the data file format can be standardized so that it can be easily read by the data analysis software, which will be described later. In some cases, commercial software has been modified to provide this standard data file output. By separating the data acquisition functions from the data analysis software, we can more efficiently analyze data from many different machines running a variety of types of tests. Since all of the computers are networked, the test data can be stored directly onto the main network file server for later analysis.

Screw-driven Load Frames

Screw-driven load frames, with capacities of up to 20 kips (89 kN) are used for tensile, compression, and flexure tests. The cross-heads on these frames have a minimum speed of 0.0002 in. (5 μm) per minute and a maximum speed of 20 in. (0.5 m) per minute. A cryostat has been designed for low-temperature tensile and compression testing to 4 K. A variety of materials is tested cryogenically, including beryllium, copper, and aluminum.

Each of the screw-driven load frames is operated by a commercial controller. Data is acquired using both commercial software and software written in-house. The test control and data acquisition is performed by a personal computer with an IEEE-488 interface to the controller. This computer is on the network, as are all of the computers in this lab. Thus, the data is stored directly onto the main file server for later analysis.

Charpy Impact Tester and Drop Tower

A standard instrumented Charpy impact machine capable of providing 300 ft·lbf (407 J) of impact energy to the specimen is used for testing to ASTM E 23, Test Methods for Notched Bar Impact Testing of Metallic Materials. In addition, several novel tests have been developed to measure coating spall behavior using this impact tester.

The drop weight tower can deliver 4000 ft·lbf (5423 J) of impact energy to the specimen. This device uses a guided drop hammer to fracture the specimen.

Impact testing is performed using standard ASTM techniques. The drop tower has had an instrumented tup added. Data are collected from both the Charpy impact machine and the drop tower using a high-speed data acquisition board in a personal computer which is networked. These data can be plotted as absorbed energy as a function of time.

Creep Frames

Creep tests are used to determine low strain rate, high-temperature material properties. Constant stress, constant load, and impression creep frames are used to perform creep tests at elevated temperatures. This involves loading the specimen essentially with dead-weights and recording the behavior of the material over long periods of time, normally hundreds of hours.

Modifications to the extensometers for the tensile creep frames have been made so that dual high-precision LVDT transducers can be mounted on each specimen. This allows for bending moments in the linkages to be averaged out of the strain signal that is recorded by the computer. Current sensitivity allows displacements of 1 μm to be measured easily. This resolution corresponds to strains of 0.01% in the current buttonhead specimen.

Data acquisition is performed by a personal computer, which can monitor and acquire data from all four frames simultaneously. The computer is interfaced to a data logger through an IEEE-488 interface. Creep data is stored directly onto the main file server. Because of this, one can monitor the progress of a creep test using the data analysis software from a computer in any office, or even by logging into a workstation from home via a modem. This is especially useful for creep tests, which normally have long durations.

Cup-forming and Formability Testing Machine

This unique machine is used to evaluate the formability of sheet materials using a hydraulic bulge test. This system is also used to fabricate small sheet metal components to very tight tolerances. Data acquisition and system control is performed through a networked DEC Micro-PDP 11/23.

Thermomechanical Process Simulator

Specimens of various configurations are tested under tension or compression in this machine. The specimens are enclosed in a vacuum-controlled atmosphere chamber during testing. The testing cycle typically consists of subjecting the specimen to a programmed thermal cycle (achieved by passing a controlled electrical current through the specimen) and simultaneously deforming the specimen in tension or compression. The specimen is held in or between interchangeable water-cooled jaws.

The load frame is capable of applying 20 kips (89 kN) to the specimen with cross-head speeds of 2800 in. (71 m) per minute. Heating rates to 105°C per second are possible with the direct resistance heating employed on this system. The maximum controlled temperature of the system is 3273 K.

The machine is interfaced with a Compaq personal computer for both control and data acquisition, using commercial software. This computer is on the network, so data are stored directly on the main file server.

Mechanical Testing Systems Network

A DEC Microvax II has been used as the foundation of a network which consists of mechanical testing equipment, personal computers, workstations, and many different peripherals. This network allows researchers to access both mechanical test data and data analysis software from their own personal computers or workstations. The network started out as a small thinwire ethernet system, connecting only the mechanical test lab and the Microvax II, as well as a couple of personal computers. It has quickly grown to a large network of over 30 personal computers and workstations, a central file server, and a variety of printers and output devices. Normal thickwire ethernet used as the backbone of the network now spans our entire facility, including labs and offices in almost every section of our group. The network is also connected to the rest of the world via Internet. This allows us to transfer data and reports to customers and collaborators in any part of the world, which has proven to be very useful in a number of ongoing programs. The computing power has been substantially upgraded with the addition of a number of DECstations, which are very fast workstations based on the RISC processor. These are used for data analysis, as well as various modeling activities which previously required Cray supercomputers. A diagram of the network is shown in Fig. 1. Since the network is constantly growing, this figure is only a partial representation.

The widest line on this diagram represents the ethernet backbone, which spans the entire building. The mechanical test frames are interfaced to the network through a variety of computers, some of which are shown in this figure. In other areas of the building, personal computers are networked. The Cisco is the local network's interface to the Internet, which is our link with the rest of the world. The computers are represented by boxes, each having its own Internet name and address. The computers are named after automobiles.

All of the data collected on the various mechanical test machines (as well as data collected in other labs in the building) are stored on the central file server, named Mustang, which has a current capacity of approximately 3 gigabytes. This can be accessed by any of the

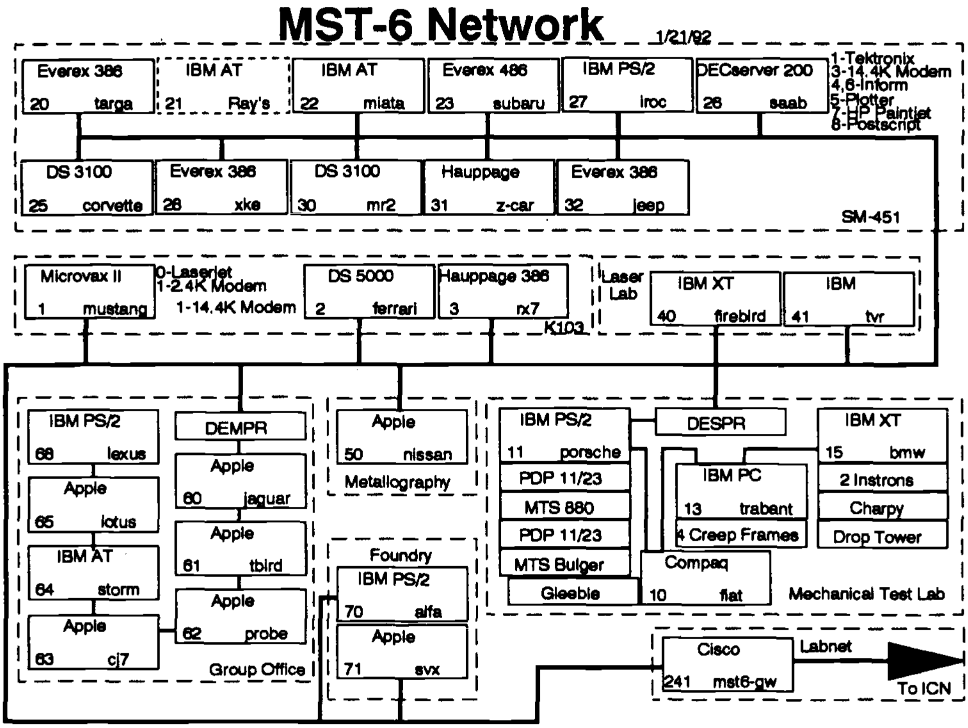


FIG. 1—*Network configuration diagram.*

computers on the network. Figure 2 is a graphical representation of this concept, showing how the various data are collected and stored on the central file server, for access by the rest of the network.

One method of access is through the data analysis system, which will be outlined in the following section. Data can also be accessed directly by any of the workstations or personal computers. For example, one could perform a specialized analysis by loading the data into a spreadsheet. This sharing of data and software is represented graphically in Fig. 3.

The network has been very successful. Members of the group in all sections of the building have used both its vast file storage capabilities and the computing power of the DECstations. The network allows the transfer of large data files quickly and easily from one machine to another. It also allows information such as data and reports to be shared easily among researchers, both within the group and outside the lab.

Data Analysis

Description of Software

A data analysis system has been developed for this mechanical test facility which allows data to be analyzed in a very efficient, accurate manner. It is flexible enough to analyze many different types of tests, and, because of its modular structure, is easily changed to analyze data using any test techniques that may be developed in the future. The software is extremely user-friendly, so everyone may analyze data, regardless of whether they have ever used a computer. This way, the researchers requesting the tests have the opportunity

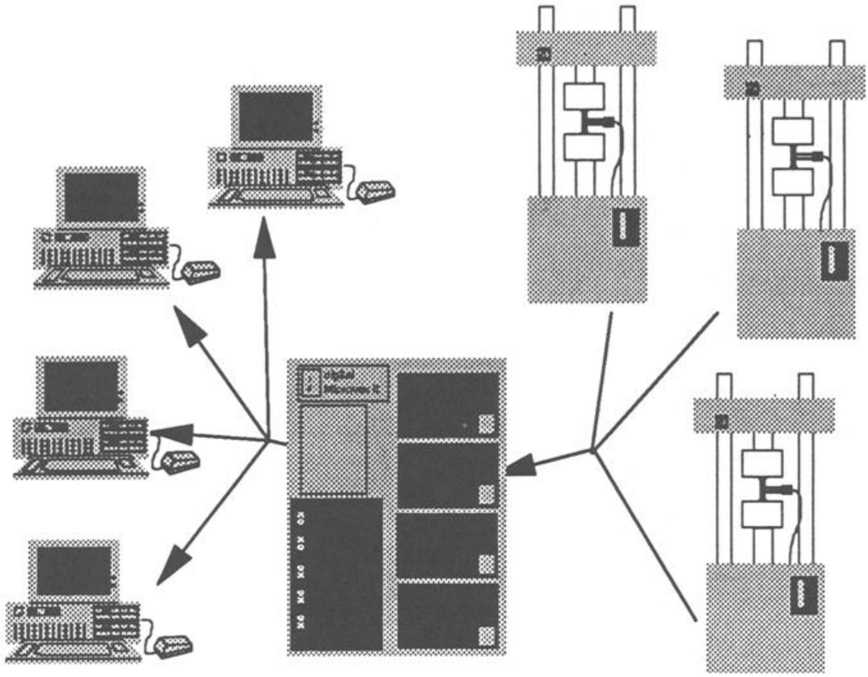


FIG. 2—*Data from tests are stored on a central file server for access by personal computers and workstations.*

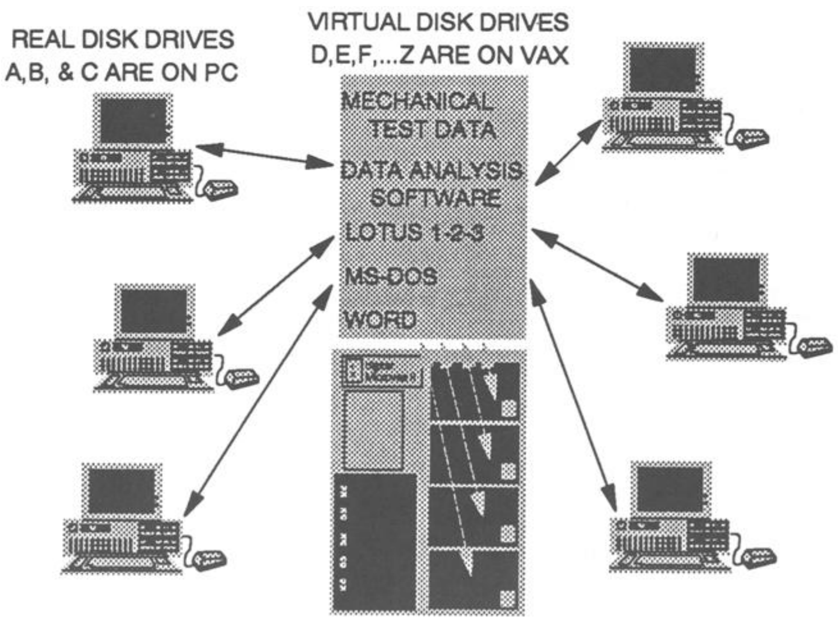


FIG. 3—*Personal computers and workstations share data and software via the central file server.*

to analyze their own results, since they sometimes know best what they are looking for in the data.

The software is easily accessible throughout the building by any of the personal computers or workstations on the network. The program uses two libraries of graphical routines called CGS and CGSHIGH which were developed at Los Alamos National Lab. The analysis software runs on the DECstations, so any computer with the appropriate graphics terminal emulation software may access it. Currently, the user interface is based on Tektronix graphics, so every computer uses a Tektronix 4105 emulator to run the software. There are plans to include an X windows user interface as well. Most user input can be provided simply by a mouse pointing device or arrow keys.

Analysis Procedure

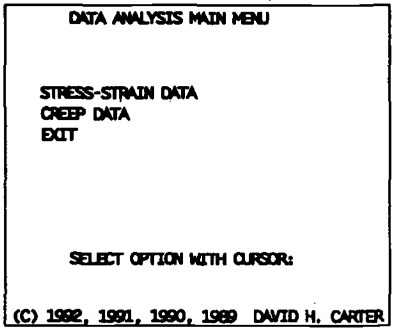
In this section, a sequence of steps performed to analyze a simple data file from a tensile test will be described. It is assumed that the user has logged in using the mechanical test analysis account password, which starts the program automatically. In screen 1 of Fig. 4, the initial screen prompts the user to input the type of test to be analyzed, a stress-strain or creep test. In this and all further cases, the user makes a selection by moving the cursor with the mouse or arrow keys and then "clicking" or hitting space.

The creep analysis routines, which will not be described here, have options similar to those of the stress-strain analysis routines. However, under the creep menu there are some additional analysis routines such as "theta-projection" programs, which use sophisticated curve fitting formulas.

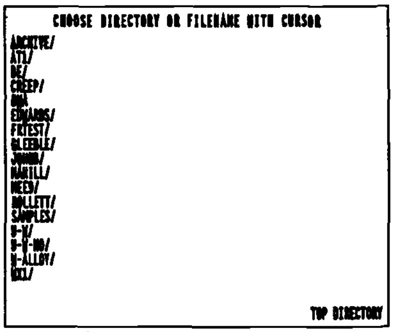
After the user selects the type of test to analyze, screen 2 prompts the user for the directory in which to find the file. These directories are normally organized by project, or sometimes by material. Screen 3 prompts for the file name within the chosen directory.

Once the user has selected the data file to reduce, the program reads the file and interprets the data. The data acquisition software on the mechanical test equipment places some important "header" information at the beginning of each raw data file. The header describes the type of test being run, the name of the test, and some other crucial information, such as specimen dimensions. The first line of this header relays to the data analysis program how many header lines there are, how to interpret the information found in the rest of the header, how many columns of raw data to look for in the file, and what each column represents. Storing the data in this fashion means the user of the data analysis software need not know any information about the data file, how it was taken, or even which machine was used to acquire the data, since the data analysis software can interpret this information from the data file.

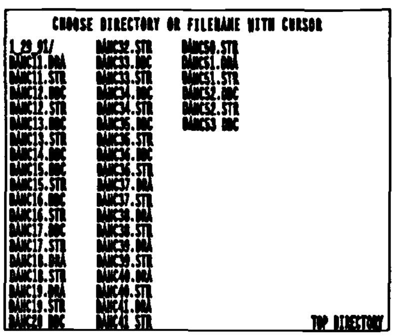
Screen 4 in Fig. 5 shows the main menu for analyzing data from a stress-strain curve. Before analyzing the data, it is sometimes necessary to edit the stress-strain data file. This is because there are sometimes erroneous data in the file. For example, after the specimen has broken, the data acquisition software may record a number of meaningless strain data points. There can also be electronic "glitches" that cause erroneous data points. Rather than editing the data by hand, or by importing it into a spreadsheet, this program allows the data to be edited graphically. The next few screens show the sequence of steps involved in one such edit operation. After "edit stress-strain data file" is selected from screen 4, screen 5 prompts for a variety of edit operations. This particular data file appears normal, except for some extra data after completion of the test. By clicking on "set min and max for curve" in screen 5 the stress-strain curve can be easily cleaned up. Screen 6 prompts for the minimum and screen 7 prompts for the maximum real data point. In these operations, the program will choose the point closest to the cursor location—the user does not have to click on the precise location of the point.



Screen 1



Screen 2



Screen 3

FIG. 4—*Sample run of data analysis program.*

Screen 8 assures that the program has chosen the correct data points by marking them with red asterisks and prompting the user to confirm that this is really what should be done. The user is also given the option to redo this operation. Screen 9 brings the user back to the edit menu and displays the edited data file. At this point, the user may continue editing or return to the main menu. If the user chooses to exit, the program asks if the data file should be stored in a "standard" format. This saves the edited stress-strain data, so that the edits do not have to be repeated every time the file is analyzed, and the raw load-displacement data do not have to be reduced again. When the data have been edited, the

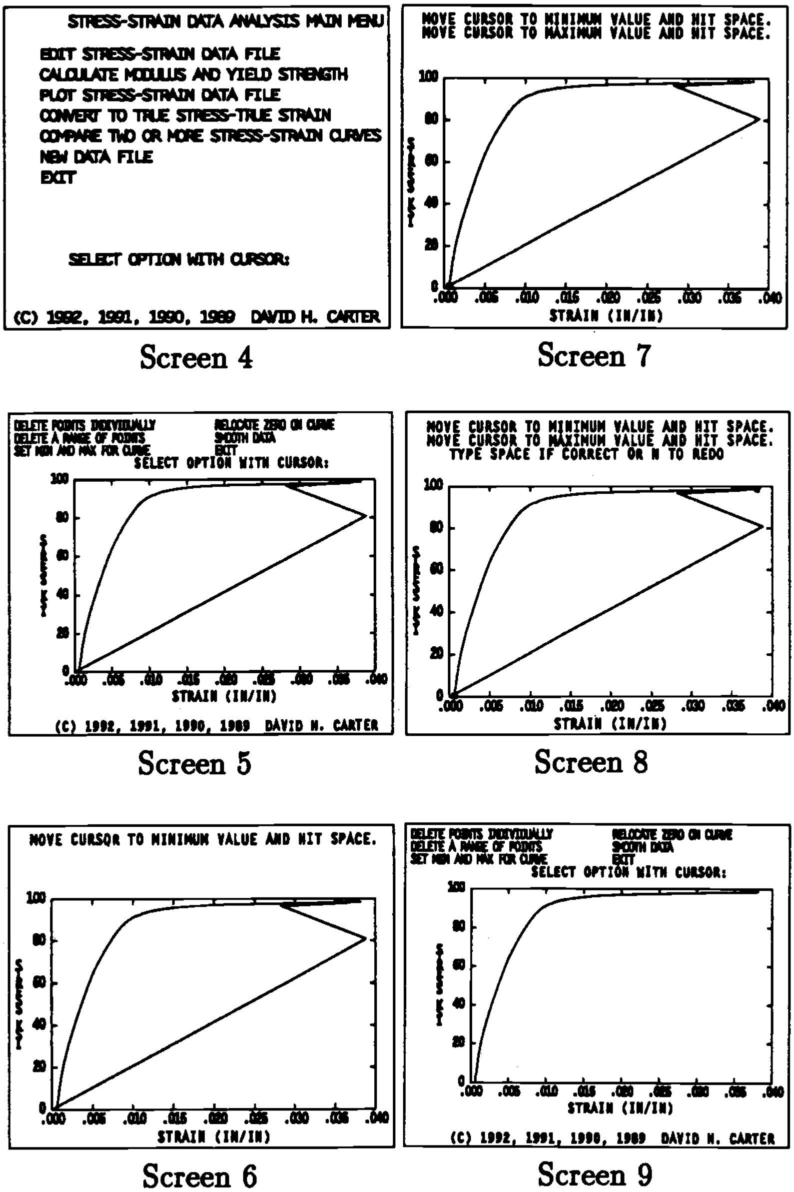
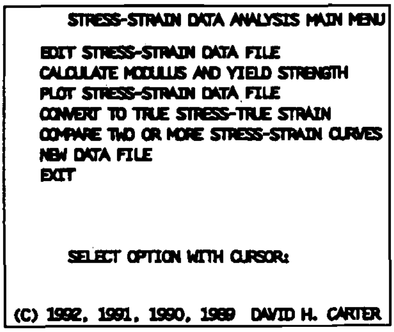


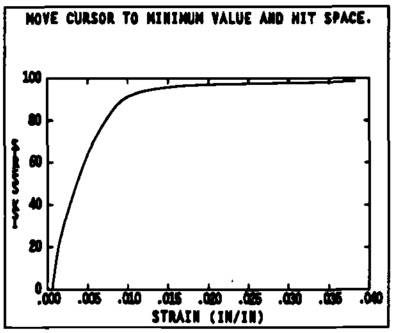
FIG. 5—*Sample run of data analysis program.*

program brings the user back to the stress-strain data analysis main menu (screen 10 in Fig. 6).

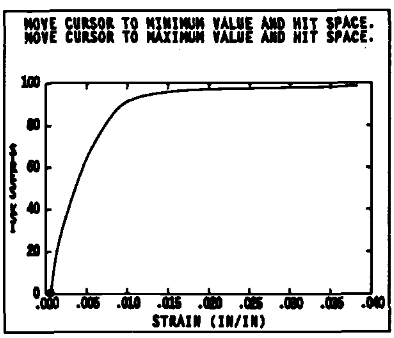
The next few screens show the steps involved to calculate elastic modulus and yield strength. There are many computer programs available to calculate modulus using a variety of numerical approaches. The modulus calculated by this program, however, is done purely based on the user choosing the correct limits between which the program calculates a linear



Screen 10



Screen 11

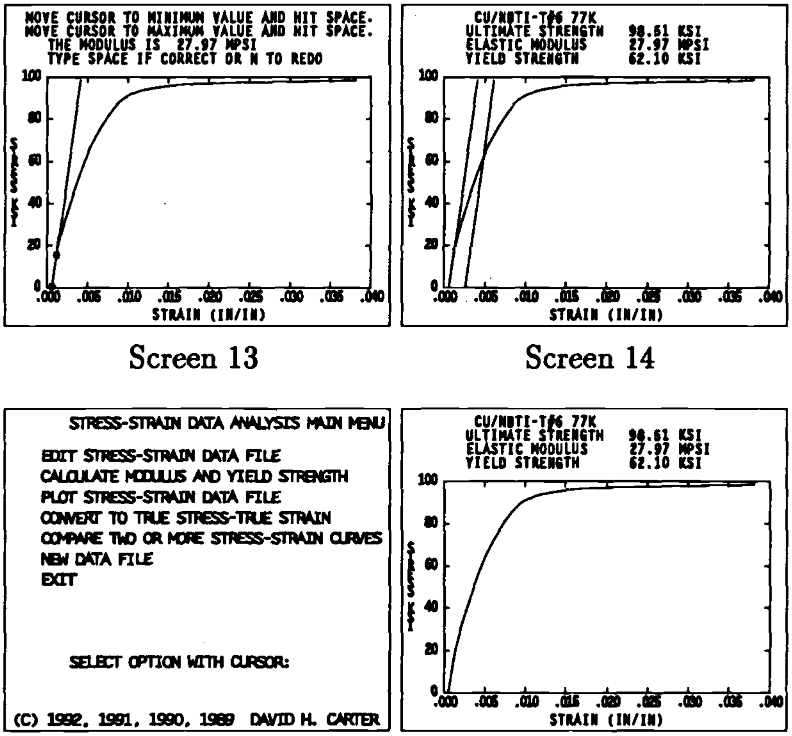


Screen 12

FIG. 6—*Sample run of data analysis program.*

fit to the data. We have found that for most of the materials that we work with, this graphical approach is the best way to calculate elastic modulus and normally provides just as accurate results as the numerical approaches.

In screens 11 and 12, the user is prompted for the minimum and maximum data points between which to calculate the modulus. The program marks these choices with red asterisks and, in screen 13 of Fig. 7, plots the calculated modulus. The minimum and maximum



Screen 13 Screen 14

Screen 15 Screen 16

FIG. 7—*Sample run of data analysis program.*

values chosen in this example are marked with asterisks in screen 13. The program also prints the value of the calculated modulus at the top of the screen. The user can choose to repeat this operation as many times as needed to assure that the calculated value is accurate. The program then asks if a yield strength should be calculated. The user is given a choice as to the offset to use in this calculation (normally 0.2%). In screen 14, the stress-strain curve is replotted, showing the modulus and yield strength lines and the calculated values of the elastic modulus, yield strength, and ultimate tensile or compressive strength, as well as the test name, at the top of the screen. The user is given an opportunity to output this to a pen plotter or other graphics output device and is then returned to screen 15.

The third option on screen 15 allows the user to simply plot the stress-strain curve without the modulus and yield strength lines, as in screen 16. If the modulus and yield strength have been calculated through option 2, the program will provide those values at the top of the screen.

The remaining menu options shown in screen 15 will not be discussed here, as they are fairly self-explanatory. The creep data analysis main menu is similar to the stress-strain data analysis main menu shown in screen 15. The creep portion of the program does include some additional curve fitting routines, which use theta projection analysis techniques. This is one method that can be used by the researcher to predict long-term creep behavior from relatively short-term creep experiments.

Concluding Remarks

This laboratory has quickly grown from a few pieces of test equipment and a couple of personal computers to a large network connecting many machines, computers, and other devices. This progress has proved extremely valuable in maintaining efficient operations. One example of the usefulness of this network is a collaborative effort with an industrial partner on the opposite side of the country. The researcher involved is able to analyze the data from mechanical tests while sitting in an office. The researcher can then write a report incorporating these data and E-mail the report across the country. In this manner, the partner on the opposite side of the country can have instant access to not just an "executive summary" of the results, but to the actual raw data from the mechanical tests.

It has been shown that this particular laboratory has integrated automated data acquisition, networking, and data analysis to provide an efficient, high-quality mechanical test facility. It is very important to address these three key factors when planning such a laboratory, especially a facility that uses a wide variety of test equipment and techniques.

David T. Heberling[1]

A Case Study: Linking an Automated Tension Testing Machine to a Laboratory Information Management System

REFERENCE: Heberling, D. T., "**A Case Study: Linking an Automated Tension Testing Machine to a Laboratory Information Management System,**" *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 40–50.

ABSTRACT: A number of issues and problems were encountered in the course of installing an automated tension testing machine and linking it to a Laboratory Information Management System (LIMS).

Difficulty was encountered in having software written to correctly calculate certain mechanical properties of steels, for which no rigorous mathematical definitions have been standardized. Additionally, it was difficult for equipment supplier and end-user to agree on how to analyze stress-strain curves having features not addressed by existing ASTM standards.

Interlaboratory comparison studies conducted with other labs in the steel industry to verify the results of the automated test machine revealed that labs are collecting data over significantly different strain ranges for their automated determinations of n values. As a result, n values do not compare well from lab to lab.

Also discussed are other details of the automation project, benefits that have been realized, and some of the laboratory's plans for the future.

It is concluded that ASTM standards require significant revision to support automated testing—not only to address the many issues that are being brought to light by automation, but also to specify automated procedures for the determination of mechanical properties.

KEYWORDS: automation, mechanical testing, yield point (YP), yield point elongation (YPE), yield strength, tensile strength, strain-hardening exponent, Laboratory Information Management System (LIMS)

Armco Steel Company's Middletown Works purchased an automated tensile tester and linked it to a Laboratory Information Management System (LIMS) as part of a project to build a "paperless" Metallurgical Laboratory (or Met Lab). Table 1 shows some highlights of this project.

The test machine purchased was a Tinius Olsen MHT 5000 lb horizontal tension tester (see Fig. 1). This machine is "semi-automatic," in that an operator measures the specimens, inserts them into the grips, and uses the DS/50 operating software to run the tests. Armco does, however, plan to eventually retrofit the machine with a robotics package to provide fully automated testing.

The LIMS was co-developed by Applied Research Laboratories (ARL) and Armco's Middletown, OH and Ashland, KY plants. The software uses ARL's CAST-VAX product, which has been extensively customized to meet Armco's specifications for the paperless operation of the two mechanical testing labs.

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TABLE 1—*Significant events of Armco Middletown Works Met Lab project.*

Date	Significant event(s)
June '89–Jan. '90	Construction of building and purchase of equipment
January '90	First equipment (including T.O. machine) relocated
Jan. '90–Nov. '90	Equipment moved in and Laboratory Information Management System developed and installed
November '90	T.O. test machine and ID equipment linked to LIMS
January '91	LIMS fully operational
March '91	Paperwork system phased out
February '92	Test machine's software altered to support editing

In the course of coordinating the Middletown Works Met Lab project, the writer has observed that many issues arise when one takes on the task of using even semi-automatic methods for mechanical testing of steels. The sections that follow describe many of these.

ASTM Issues

Many of the issues that arose had to do with setting up the machine's software so that the automated tests of Armco's steel products would conform to ASTM standards. Unfortunately, the applicable standards were found to be nonspecific in certain areas—particularly those having to do with the phenomenon of yield point elongation (YPE), which is encountered daily in the Armco Met Lab.

FIG. 1—*Tinius Olsen MHT 5000 lb tensile test machine (left) with PC, printer, interfaced calipers and micrometers (center right), and interfaced hardness tester and auxiliary LIMS terminal (far right).*

Measurement of YPE

The most obvious question regarding YPE is how it should be measured by software. Consider the following definitions from ASTM E 6, Definitions of Terms Relating to Methods of Mechanical Testing:

Yield point elongation, YPE—in materials that exhibit a yield point, the difference between the elongation at the completion and at the start of discontinuous yielding.
Yield point, YP [FL^{-2}]—the first engineering stress in a test in which stresses and strains are determined for a material that exhibits the phenomenon of discontinuous yielding, at which an increase in strain occurs without an increase in stress.

Referenced by these definitions are two figures that show that the region of a stress-strain curve in which the stress alternatively increases and decreases (or remains constant) is considered discontinuous yielding. The following questions, however, are not addressed:

(1) How should one characterize a curve having an inflection (a hint of the mechanical behavior leading to YPE) yet no region over which the stress actually remains constant or decreases? (See Fig. 2*a*.)
(2) How can one program software for detection of even borderline YPE without risking detection of false indications? (See Fig. 2*b*.)
(3) In cases where there is a gradual transition back to normal strain hardening, what is the end of discontinuous yielding? (See Fig. 2*c*.)

Armco's solution to Question 1 has been to use the term "inflection" to describe such curves and to treat materials exhibiting inflection as if they have a very small amount of YPE.

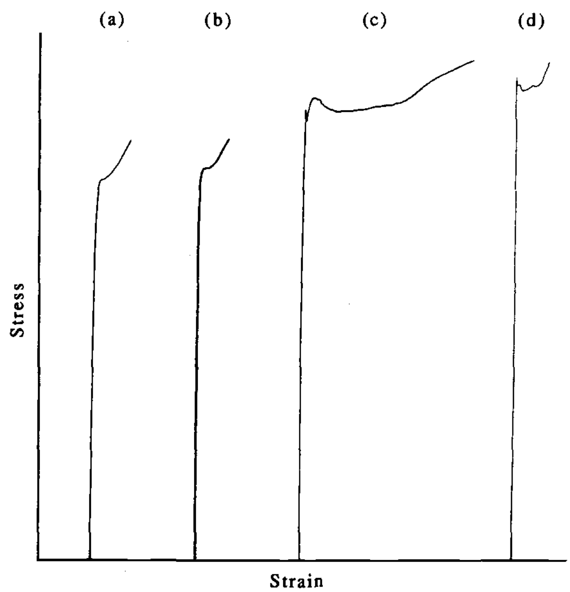

FIG. 2—*Low-magnification stress-strain curves of flat-rolled carbon steels. Curve* (a) *exhibits inflection,* (b) *shows a small amount of YPE, and* (c) *has much YPE and a gradual transition to strain hardening. Curve* (d) *is a more typical example of YP and YPE.*

Question 2 is not resolved. The existing software, like most, requires a small load drop to detect YPE, so YPE measurement is accurate most, but not all, of the time. A few times a day, cases are seen in which real load hesitations *are not* detected (see Fig. 3), and once in a long while a false indication is detected. Such incorrect results are edited manually by the operator.

Question 3 has been resolved by agreement to use the point of maximum slope during the transition as the end of YPE. This is fairly straightforward to do in manual and in automated testing, but one must recognize that many labs in the industry do not subscribe to this practice.

Validity of Yield Strengths When YPE is Observed

Another issue faced early in the automation project was how to report yield properties for materials exhibiting YPE. Consider the following note from ASTM E 8, Test Methods of Tension Testing of Metallic Materials:

> Note 16—If the load drops before the specified offset or extension-under-load is reached, technically the material does not have a yield strength (for that offset or extension-under-load), but the stress at the maximum load attained before the specified offset or extension-under-load is reached may be reported instead of the yield strength.

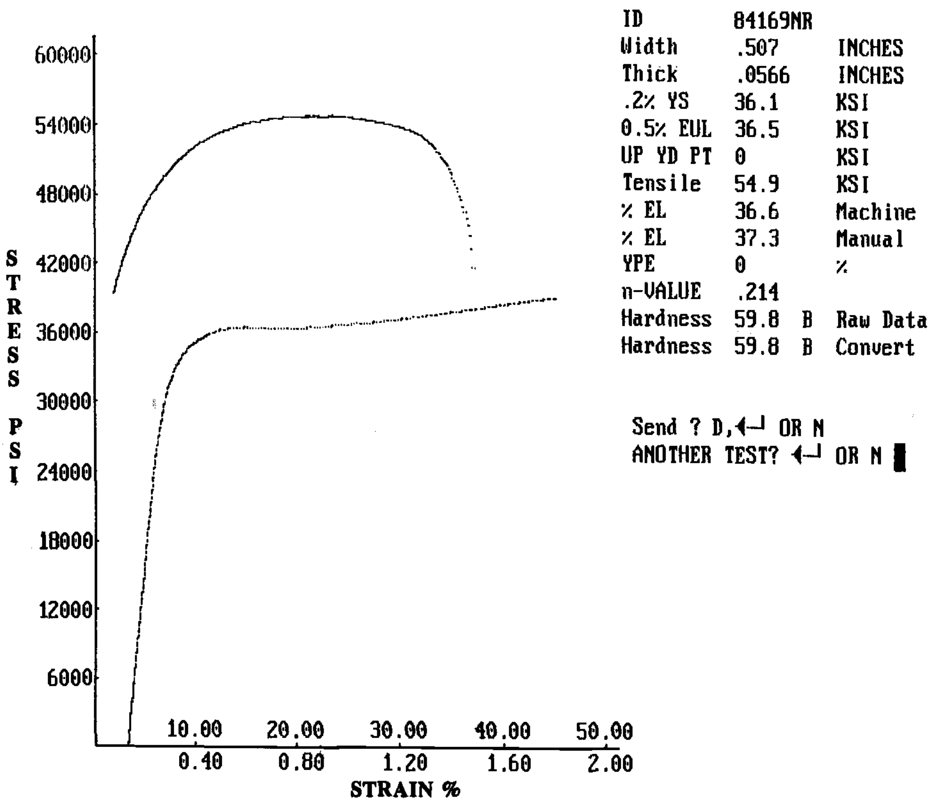

FIG. 3—*Printout from a test in which the stress decreased a very small amount, but not enough for the software to register YPE.*

The test software originally reported 0.2% offset yield strengths and 0.5% extension-under-load yield strengths for all tests, regardless of whether or not the material exhibited YPE. Since this contradicted Armco procedures and the aforementioned note, Armco had the software altered by the supplier. Today, yield properties are reported as follows:

	0.2% Offset YS	**0.5% EUL YS**	**Upper Yield Pt.**
If there is no YPE:	Reported	Reported	Not Reported
If there is YPE:	Not Reported	Not Reported	Reported

This practice is consistent with ASTM E 8's note and with Armco procedures for manual testing that have been established for years. Yet most equipment suppliers and end-users have not adopted similar practices, presumably because: (1) it is difficult and tedious to explain to all of one's customers why offset or EUL yield strengths are not determined in some cases, (2) it is simpler to write software to always calculate the same results, and (3) many rarely deal with materials exhibiting YPE.

Interestingly, now that the issue has come up in ASTM E-28 Committee meetings, many have taken exception to the wording of Note 16, and the end result is that a replacement note is being balloted. Obviously, the validity of offset and EUL yield strengths for materials with YPE must be decided, if ASTM wishes to have comparable results reported from lab to lab.

Upper and Lower Yield Points

In order to conform to ASTM standards, the software for the new test machine was set up to determine (upper) yield points for materials exhibiting YPE. ASTM E 6 and E 8, it is noted, do not mention "lower yield point," although this property is routinely determined by many laboratories, particularly those in the steel industry.

Since lower yield point is not defined, one could conclude that labs reporting only lower yield points for materials exhibiting YPE are not testing to ASTM standards. And, strictly speaking, reporting of *upper* yield point is not to the letter of ASTM E 6 or E 8, because the word "upper" isn't recognized. Note, however, that the ASTM E 6 and E 8 definitions of yield point do describe the property that is generally called upper yield point.

If upper and lower yield points are in use and are perfectly valid to report, at least in certain instances, then the applicable standards should be revised to recognize and define both terms.

Consideration of Yield Point in Calculation of Tensile Strength

Another issue regarding use of software to calculate mechanical properties is whether or not a high (upper) yield point should be considered when calculating a material's tensile strength. This is a concern, because some higher strength carbon steels, when tested on a stiff machine, exhibit an upper yield point that reaches a stress greater than any sustained in the remainder of the test (see Fig. 4). Software written to simply look for the highest force registered will, for such a material, use the force at the yield point as the basis for the tensile strength calculation.

Consider the following excerpts from ASTM E 6 and E 8, respectively:

Tensile strength, S_u $[FL^{-2}]$—the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross-sectional area of the specimen.

Tensile Strength—Calculate the tensile strength by dividing the maximum load carried by the specimen during a tension test by the original cross-sectional area of the specimen.

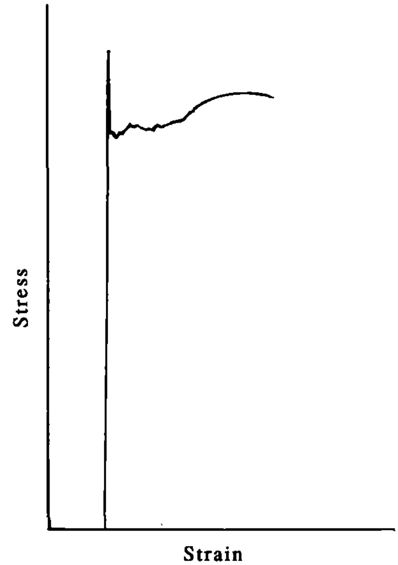

FIG. 4—*Sketch of a type of stress-strain curve sometimes obtained for high-yield-point carbon steel products. (The yield point happens to be the highest stress measured in the test.)*

The real issue is how the tensile strength of high-yield-point materials *should* be defined. This has been discussed in ASTM E-28 meetings, and the consensus seems to be that the tensile strength definition should not be altered, but that a note should be added to ASTM E 8 stating that the highest load *after discontinuous yielding* is often used.

Strain Range Over Which Strain-Hardening Exponent is Calculated

Soon after the Met Lab began using the test machine to determine the strain-hardening exponent (n value) of steels, it was reported that Armco's results ran lower than those a competitor determined for similar material. Interlaboratory comparison studies verified this and indicated that the differences were caused by data for the n value calculation being collected over different strain ranges. Examples of ranges in use include:

Initial Strain, %	**Final Strain**	**Comments**
10	Strain at max. load (>20%)	Range first used by Met Lab.
10	20%	Used by other labs.
5*	Strain at max. load (>20%)	Currently used by Met Lab.
6*	12%	Used by a competitor.

*When the material to be tested may have YPE, provisions must be taken to delay the collection of data for the n value calculation until after completion of YPE.

It is useful to compare the strain ranges shown to the following specifications of ASTM E 646, Test Method for Tensile Strain-Hardening Exponents (n-Values) of Metallic Sheet Materials:

> Record the load and corresponding strain for at least five equally spaced levels of strain (Note 9) encompassing the range of interest specified in the product specification. Usually, the greatest of these strains is at or slightly prior to the strain at which the maximum load occurs, and usually the lower bound of these strains is the yield strain (for continuous-yielding material) or the end of yield-point extension (for discontinuous-yielding material).

After consulting with Armco Research, it was concluded that the strain range over which data are collected has a significant effect because of deviations from the ideal relationship between true stress and true strain. Log/log plotting of true stress versus true strain theoretically produces a straight line, but such is often not the case in practice.

For some steels, the log/log curve decreases in slope with increasing strain (see Fig. 5.) Since the *n* value is the slope of the best-fit line, there is, for such materials, an inverse relationship between the strains used and the resulting *n* values. There are, however, steels for which the curve deviates from linearity in the opposite manner. For these, the relationship between strains and *n* values is not an inverse one.

To comply with the intent of ASTM E 646 and, for some steels at least, to avoid reporting overly conservative *n* values, the lower limit of the strain range used for the Met Lab's *n* value calculations has been reduced to 5% (or 3% beyond the end of YPE, for materials with discontinuous yielding).

This information is evidence that ASTM E 646 should be revised to specify the strain range in more definite terms or to require that the strain range be reported along with the *n* value.

Need for Automated Procedures

Several ASTM standards on mechanical testing do not yet include specific procedures for automated testing, although some revisions to this end are currently being prepared or balloted.

Several paragraphs are about to be added to ASTM E 8, for example, to support reporting of automatically determined elongation at fracture as percent elongation. This will be significant, because many labs with fully automated equipment have already been using this practice for years.

Revisions to support automation are just now being drafted and balloted for other mechanical testing standards, and there may be many standards for which such revisions have not even been considered yet.

The writer's point is that ASTM subcommittees and task groups in charge of mechanical testing standards should be initiating any revisions needed to support the automation of mechanical testing. And to support such efforts, those who are interested in automation and related issues are encouraged to attend meetings and make their opinions known.

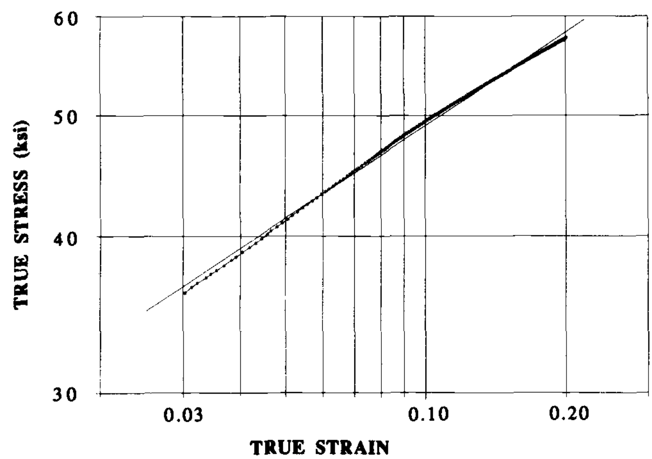

FIG. 5—*Log/log plot of true stress versus true strain for a carbon steel. The materials' n value, by definition, is the slope of the best-fit line.*

Other Issues and Details

Many technical issues not directly related to conformance to ASTM standards also arose in the course of automating. Some of these are discussed in the following sections.

Data Integrity and Retention

When paperwork is no longer used for routine reporting of all test results, several issues related to data integrity and record keeping arise.

How, for example, can results be edited, such that an audit trail will be maintained? Certainly, allowing users to alter results without at least having a record of the event will be neither desirable nor permissible. Armco's solution resembles the paperwork practice of drawing a single line through the incorrect result and adding the correct one, plus the editor's initials and the date. Both LIMS and the test machine software permit users to revise results, but both original and edited results are stored, along with a record of who did the editing and when. Comment fields are used to explain what was done and why it was necessary.

There is also the matter of long-term storage of results. Armco does this electronically, using a variety of techniques to minimize the chances of any data being lost. Disk shadowing and daily backups are used for in-process data, and finished results are uploaded to Armco's corporate IBM system, which writes the data to discs for long-term retention.

Less unique to paperless operation, but important nevertheless, is the issue of what *not* to retain, which includes inapplicable results and digits in excess of those which are "significant." Inapplicable results may be simple to avoid reporting in manual testing, but this may not be the case when one automates. This depends on the software, which should be advanced enough to recognize, and suppress printing of, such results.

Significant digits should also be handled appropriately. The following is an example, in which units are academic: Suppose a yield load of 585 is divided by a width of 0.498 and a thickness of 0.0482. It would be improper to report the yield strength as 24 371.344. The correct result, which should have three significant digits, would be 24 400. To round results as such, the Met Lab has had some changes made to the test machine software. In addition, a format table within LIMS ensures that results are rounded appropriately before reporting or uploading.

Communications

In linking the test machine to the LIMS, Armco opted to use simple, one-way communications. Fixed-format messages are transmitted via an RS232 connection, using DECnet and LAT. No handshaking protocol is involved, so the machine neither expects nor receives response from the host (LIMS) system. This approach is simple and straightforward, but it sacrifices the ability for the test machine to obtain, from LIMS, information about the specimen that is to be tested.

Since LIMS cannot tell the test machine what type of test to run, this information is conveyed by adding groups of letters (called suffixes) to identifications (called Lab IDs) which are permanently stamped onto test pieces (see Fig. 6.) These suffixes tell the operator which test parameters to select, and upon testing, they are sent to LIMS as part of the specimen ID, to indicate what test has been run.

One-way communication can cause problems when the communication link goes down, because both machine and operator may be oblivious to the fact that results are not being received. This has happened in the Met Lab, but each instance was discovered within a day or two, and results were promptly recovered from the PC and hand-entered into LIMS. To minimize this sort of confusion, Armco is having the LIMS software altered to generate error messages alerting lab personnel when the communication link goes down.

FIG. 6—*Photograph of a Lab ID and suffix stamped on a standard ASTM tensile specimen. (The "N" indicates that an n value must be determined.)*

Other Technical Details

As was mentioned previously, permanent Lab IDs are stamped onto test blanks as they are sheared from larger samples. These identifications are lab serial numbers, consisting of five-digit numbers and suffixes of up to three letters. The stamping of these is supported by LIMS, which specifies the Lab IDs and cross-references them to coil identifications, and by PINSTAMP[2] equipment, which stamps the characters transmitted by LIMS. This has been an effective means of permanently identifying specimens.

A testing detail worth mentioning is that an *X-Y* recorder is used as a backup to the test machine's DS/50 software. The recorder's curves are rarely needed, but once in a long while the software miscalculates a result or a test is aborted. In such cases, it is very helpful to be able to manually calculate results using the plotted curves, because this may save the lab from machining extra specimens—or in some cases from having a coil of steel run across an extra production unit to obtain new samples!

One final detail that had to be addressed in the automation project was when, during a test, to have the control software increase the speed of testing for the tensile strength determination. For materials without YPE, this can be done immediately after the offset yield strength or extension-under-load yield (or both) is obtained. If YPE is to be measured, however, the increase must be delayed until after the end of YPE. The difficult question, then, is how much "normal" strain hardening must be observed before the software can conclude that YPE has ended.

For carbon steels, Armco has found that an additional 1.5 to 3% strain must be plotted at the pre-yield speed, without any hint of YPE, before the speed can be increased. If the user is content to miss some additional YPE less than 1 time in 100, the increase may be done 1.5% after the last hint of YPE. If, however, the user wishes to be sure that no YPE is missed, as in an R&D environment, the speed should not be increased until at least 3% strain is plotted after the last hint of YPE. The former approach is in use at Armco's production labs, and the latter is being used at Armco Research.

Benefits of Semi-Automatic Testing

The following are some of the benefits Armco has realized as a direct result of installing the automated test machine and linking it to the LIMS:

- Automatic determination of 0.2% offset yield strength, *n* value, and percent elongation.
- Support of, and simple switching between, ASTM and JIS testing (the latter is a requirement for some Armco customers).
- Results stored and recalled by date, test, or operator, or a combination thereof.

[2] PINSTAMP is a registered trademark of Telesis Marking Systems, Chillicothe, OH.

- Automatic transmission of results to LIMS.
- Improved throughput/reduction of turnaround time.
- Improved repeatability and reproducibility.

Plans for the Future

Automatic Measurement of r *Values*

At the time the testing machine was purchased, transverse extensometers for use in automatic determination of *r* values were being developed by the manufacturer. However, such an extensometer was not purchased, because Armco wished to allow time for further development and because it was known that such a device could be added at a later date. This addition may be accomplished in the next few years, depending largely on customer demands and business conditions.

If a transverse extensometer *is* added, other changes may also have to be made. If transverse measurements are to be taken only in the center of the reduced sections, for example, the reduced section length will have to be increased to 3 in. to comply with ASTM E 646. This will require changes to the fixturing and CNC programs that are used in the milling of specimens.

Possibility of Fully Automating the Equipment

Armco plans to eventually convert the Tinius Olsen machine to fully automatic (robotic) operation, which can be accomplished by installing a robot arm where the operator stands or sits today. Such a robot arm has already been incorporated into systems sold by the manufacturer (see Fig. 7).

The Met Lab's fully automated system would:

- Obtain specimens from pre-loaded racks.
- Read the IDs stamped on the specimens.

FIG. 7—*A test machine that has been fully automated by adding a robotic arm.*

- Select test parameters based on the ID suffixes.
- Measure thickness and width of the specimens.
- Determine the material's Rockwell hardness, using a machine-selected scale (based on the thickness and expected hardness).
- Insert the specimen into the grips.
- Run the test and transmit all results to LIMS.
- Remove and discard the specimen halves.

From Armco's perspective, adding the robot arm appears to be a simple task, compared to resolving some of the associated issues, such as:

- The need for a hardness tester capable of setting up its own scales, possibly involving different indenters.
- Difficulty involved in using optical character recognition (OCR) to read IDs stamped onto a variety of types of surfaces.
- The need to enhance (and nearly perfect) the operating software before beginning robotic operation.

Conclusions

(1) ASTM standards on mechanical testing do not yet give sufficient guidance regarding automation, so it is difficult to ensure that automated testing conforms to all applicable standards. Assuming that ASTM's desire is to provide for a smooth transition as automated testing is adopted around the world, its committees should work to resolve automation issues before equipment suppliers and uses institutionalize their own solutions.

(2) The phenomenon of YPE needs to be addressed in more depth in ASTM E 6, E 8, and other standards. Items requiring clarification include: how YPE should be measured, whether offset and EUL yield strengths are defined for materials with YPE, whether lower yield point is an acceptable property to report, and how tensile strength should be calculated when the yield point is the highest stress measured in the test.

(3) The strain range over which data are to be collected for use in n value calculations needs to be standardized better than it is today. The guidelines of ASTM E 646 apparently are not specific enough to ensure that all labs testing to that standard obtain comparable results.

(4) To avoid confusion associated with the aforementioned concerns, purchasers of testing software should specify (or at the very least, ask) exactly what the software will do. Upon installation, provisions must be taken to verify the software's performance before using it in routine testing.

(5) Issues concerning data integrity, record retention, communications and identification, as well as countless other technical details, must be addressed when the automation of mechanical testing is attempted.

(6) Benefits of automated testing can include: automatic performance of complex calculations, flexibility, electronic result storage, automatic transmission of results, increased throughput, and improved repeatability and reproducibility.

Rashid N. Khan[1]

Data Interpretation Issues in Automated Mechanical Testing

REFERENCE: Khan, R. N., **"Data Interpretation Issues in Automated Mechanical Testing,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 51–64.

ABSTRACT: Sources of errors in mechanical testing attributable to the test instrument and transducers are generally well-understood. ASTM and other standards organizations have well-defined procedures for the calibration of load, strain, and displacement transducers, and the technology for improving the accuracy of these transducers has improved greatly in recent years. However, the calculation of mechanical properties is still highly dependent on the interpretation of stress-strain curves by humans, and the variation in human judgment leads to errors which in many cases are considerably greater than the errors in the transducers used for acquiring stress-strain curves. The problem is further compounded by the fact that ASTM test procedures poorly define mechanical properties, and most of these definitions are qualitative rather than quantitative. The lack of good definitions becomes most apparent when the definitions are translated into numerical algorithms for computerized systems that try to compute mechanical properties without the benefit of human judgment. This paper presents examples of these poor definitions and explains how they can lead to substantial errors in computing mechanical properties even if the stress-strain curve is highly accurate. Definition errors in the calculation of Modulus, Yield Point, Proportional Limit, Break Point, and other commonly used mechanical properties are described. The paper concludes by presenting some computer algorithms to improve the quality and consistency of computing mechanical properties from stress-strain curves.

KEYWORDS: data interpretation, mechanical properties, mechanical testing, numerical algorithms, stress-strain curves, modulus, yield point, proportional limit, break

ASTM and other organizations concerned with testing standards have established elaborate procedures for the significant and critical aspects of mechanical properties testing which could produce variation in results. These aspects include calibration of transducers, specimen preparation, specimen conditioning, environmental control, dimensions, and tolerances, etc. The mathematics required to compute results and statistics is well-covered and unambiguous. One critical aspect that has not been fully addressed is the precise definition of algorithms for determining critical regions or points on stress-strain curves which defy simple mathematical definitions. For example, there is no mathematical definition of any of the following points or region in any ASTM test method: Young's Modulus region, proportional limit point, yield point, lower yield point, and break. The selection of these points or regions is generally left up to the judgment of the individual interpreting the stress-strain curve and no algorithms exist for selecting these points in a consistent, reproducible fashion.

The technology used in testing machines has improved tremendously over the past decade. Many vendors now offer test machines with transducer accuracy better than ASTM speci-

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fications. However, the benefit of these highly accurate machines are negated if there are no well-defined algorithms to compute critical points. An accurate test machine can produce accurate stress-strain curves; it can not produce accurate information such as modulus and yield if the algorithms are not accurate, well-understood, or consistently applied. The purpose of testing standards is to ensure reproducibility of data. However, if test results are dependent on the judgment of an individual, the data cannot be adequately reproduced. This defeats the purpose of testing and standards.

Lack of well-defined algorithms is not new; there never were any algorithms. Thus, one might wonder why this problem is coming to surface now. There are several reasons for this:

(1) Most test standards and definitions have evolved from metals testing. Metals generally exhibit well-defined behavior. Thus, the modulus region of traditional metals is fairly well-defined and linear and the failure of metals is generally sharp and unambiguous. However, starting with plastics, the world has witnessed the emergence of a large number of new materials that do not exhibit well-defined behavior. The stress-strain curves of many types of new materials have very short linear regions or do not have any linear region. Similarly, many new materials exhibit gradual failures making it difficult to identify the failure point.

(2) The rapidly increasing use of computers and software to analyze data has forced the development of algorithms. In some cases the algorithms produce results that are not consistent with the judgment of users. In other cases, the use of different algorithms by different software packages has produced inconsistent results. These inconsistencies are forcing the issue of algorithms to the forefront.

(3) Data acquisition and transducer conditioners in new generation test machines have become very accurate. However, consistency of information has not improved at the same pace, partly because of the lack of standard algorithms. Organizations that have invested in expensive, highly accurate test machines naturally demand increased accuracy and consistency. Regardless of how accurate a stress-strain curve is, the computed results will not be consistent if different algorithms are used.

(4) Traditional mechanical test data were best presented via load-elongation curves plotted on strip-charts. These data were "continuous" in nature and not easily prone to precise numerical algorithms. Newer generation test systems present test data in arrays of load-elongation pairs which are much more suitable for numerical algorithms. If the algorithms are not consistent, the end results will not be consistent either.

The Need for Algorithms

In this paper, we will limit our discussion to some of the commonly used material properties that are judgmental in nature. Thus, for example, "peak stress" is not judgmental because it is simply the peak value of a stress-strain curve and is unambiguous. The same is not true for other commonly used mechanical properties such as:

(a) Linear portion of the stress-strain curve used to compute Young's Modulus or Tangent Modulus
(b) Break Point
(c) Yield Point
(d) Proportional Limit Point.

Let us examine the current ASTM definitions of these properties and problems to which these definitions lead.

Young's Modulus and Tangent Modulus

A variety of ASTM test standards require the calculation of Young's Modulus or Tangent Modulus. ASTM D 638 (Test Method for Tensile Properties of Plastics) defines Modulus of Elasticity as the slope of the ". . . initial linear portion of the load-extension curve. . . ." In the Annex A1.7 of D 638 one finds the following cautionary note: "The stress-strain curve of many plastics do not conform to Hooke's law throughout the elastic range but deviate therefrom even at stresses well below the elastic limit. For such materials the slope of the tangent to the stress-strain curve at a low stress is usually taken as the modulus of elasticity." ASTM D 3039 (Test Method for Tensile Properties of Fiber-Resin Composites) requires the computation of the Modulus of Elasticity but does not define the "linear portion of the curve." ASTM D 3379 (Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials) specifies the Young's Modulus but defines it only as the slope of the "straight line section" of the load-extension curve. ASTM D 3410 (Test Method for Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites) requires the calculation of Compressive Modulus as the "slope of the initial straight linear portion of the stress-strain curve" with no further elaboration. ASTM D 790 (Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials) specifies the Tangent Modulus of Elasticity which is to be ". . . calculated by drawing a tangent to the steepest initial straight line-portion of the load deflection curve." ASTM E 9 (Compression Testing of Metallic Materials at Room Temperature) refers to E 111 (Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus) which characterizes Young's Modulus as ". . . calculated from the load increment and the corresponding extension increment, between two points on the (straight line) as far apart as possible."

All of these definitions are qualitative and highly subject to individual interpretation. Many significant issues are unanswered such as: What is straight? How long a line segment is to be used to compute a slope or tangent? How far apart is far apart enough? Who decides? How is it reported?

To further illustrate this point, Figs. 1*a* and *b* show the stress-strain curve of the same test specimen. The modulus line is shown for the curves along with the region of the curve used to compute the slope using linear regression. For all practical purposes the modulus line for the two curves is reasonable. Yet the Young's Modulus value for Figs. 1*a* and *b* is 135.9 MPa and 126.6 MPa, respectively. The variation in results is in excess of 7%.

Break Point

None of the ASTM test procedures studied by the author provides any definition of the break point. Most ASTM test methods assume that the calculation of the break point is easy because it is the point where there is a sudden drop in load. However, in reality, materials exhibit a variety of behaviors ranging from a sudden rupture, which is easy to determine, to a gradual failure. In the latter case it is very hard to precisely determine the break point. An example of such a gradual failure phenomenon is reflected by the load-elongation curve presented in Fig. 2 for which it is not possible to determine the point at which there is a sudden drop in load. Some composites also exhibit "step wise" failure for which it is difficult to agree on a break point.

Yield Point

ASTM E 8 (Test Methods of Tension Testing of Metallic Materials) defines yield point as "the point at the top of the knee or the point at which the curve drops." ASTM E 9 says

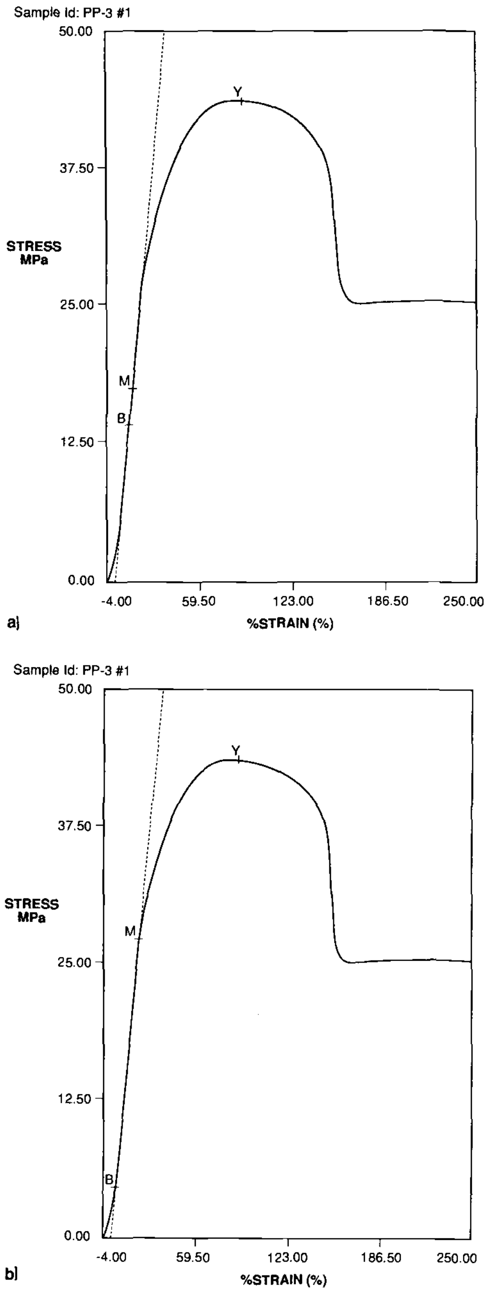


FIG. 1—*Young's Modulus* (a) *equals 137.87 MPa,* (b) *equals 126.64 MPa.*

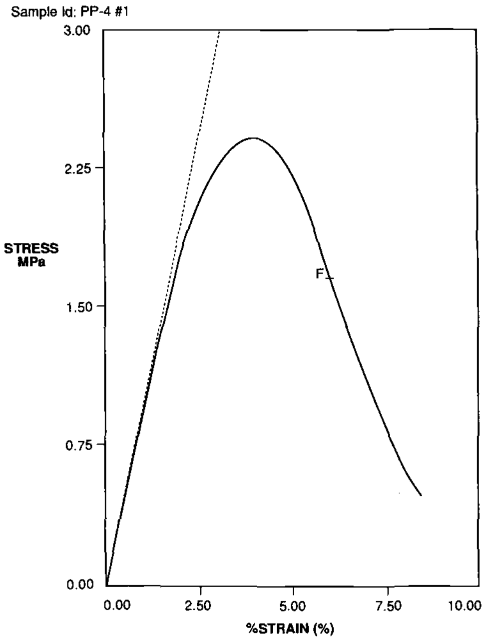


FIG. 2—*Undefined break point.*

yield point is "the maximum stress attained just prior to the sudden drop in stress." ASTM D 638 defines yield point as being "the first point in the stress strain curve at which an increase in strain occurs without an increase in stress." All of these definitions leave a lot to individual interpretation. Indeed, merely by changing the scales used to present a stress-strain curve, one can make the same individual select different points as the yield point for the same specimen. An example of this problem is illustrated in Figs. 3*a* and *b*. These figures represent the load-elongation curve of the same specimen. In Figs. 3*a* larger *x*- and *y*-axis scales are used and the yield point *Y* is selected at an appropriate place resulting in a yield elongation of 85%. In Fig. 3*b* the same data are presented but using much smaller values for the *x*- and *y*-axis scales. The slope of the curve now looks different resulting in the selection of a different yield point with a yield elongation of 81%. Merely changing the scales changes the value of yield elongation by almost 5%. This is possible only because the present definition depends on the judgment of users, and this judgment is affected by how the data are presented.

Proportional Limit Point

ASTM D 638 Annex A1.14 defines "proportional limit" as the "greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain." ASTM E 6 (Definitions of Terms Relating to Methods of Mechanical Testing) has an identical definition for proportional limit. A note in ASTM E 6 states that "Many experiments have shown that values observed for the proportional limit vary greatly with the sensitivity and accuracy of testing equipment, eccentricity of loading, the scale to which the stress-strain diagram is plotted. . . ." Like the yield point and the modulus region, the proportional limit point is not well-defined. It is left up to the individual analyzing the data to determine at which point the curve deviates from straight line behavior.

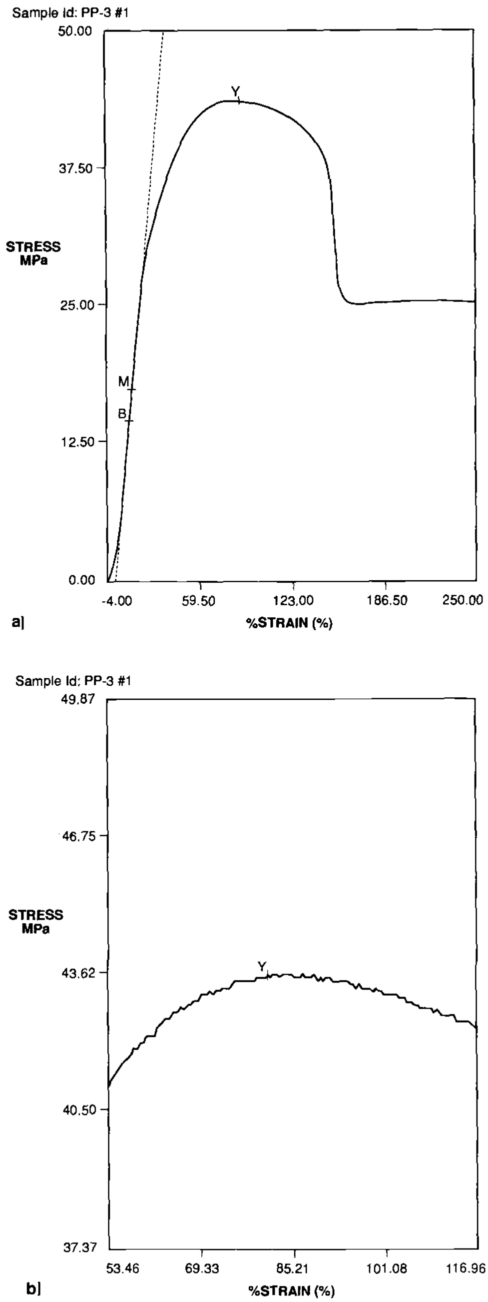


FIG. 3—*Yield elongation* (a) *85%,* (b) *81%.*

Proposed Algorithms

The rapid development of software and computers over the past decade has made it possible to develop sophisticated algorithms at an affordable price. In an attempt towards standardization we have developed a set of such algorithms. These algorithms form the basis of a proposed ASTM Standard Guide for the Data Interpretation of Computerized Stress-Strain Curves which is presently being reviewed by ASTM Committee D20 on Plastics, Subcommittee D20.25. The remainder of this paper describes some of the key algorithms to illustrate some useful ways of developing standard algorithms.

Finding the Linear Portion for Modulus

The algorithm presented here defines a repeatable mathematical procedure for determining the linear portion of the stress-strain curve and its slope. Once the slope is known, the toe compensation, Young's Modulus, Tangent Modulus, as well as many other properties may be computed with minimum uncertainty. This algorithm determines the *maximum slope* over the *longest segment* of the force-elongation curve. A two-step algorithm is used for computing the linear portion of the curve.

Input Parameter

The following parameter must be specified and explicitly reported when this algorithm is used:

(a) % Tolerance (*%T*). In units of percent. Typical suggested value of 2%.
(b) % Segment Length (*%SL*). In units of percent. Typical value of 5% or 5 data points, whichever is longer.
(c) Optional Starting Point (A) and Ending Point (B)

The optional points (A) and (B) represent the boundaries of the stress-strain curve between which the modulus segment will exist. They may be used to limit the region over which the slope should be determined. For example, the Starting Point may be a force value below which it is not advisable to search for slope because of noise considerations. In most cases, the Ending Point is also a force value or yield point. The Starting and Ending Points may be expressed in units of force, stress, or strain.

Step 1: Determine Cut-off Point (Fig. 4*a*)

(1) Find the elongation (El_{pk}) from start-of-test to peak force.
(2) Define Segment Length SL = MAX{(1% of El_{pk}) or (5 data points)}.
(3) Beginning from Starting Point A find a data segment of length SL.
(4) Compute the slope of this segment using a first-order linear regression.
(5) Find the next segment of length SL by moving over 5 data points and compute its slope.
(6) Repeat this process till the slopes of all segments of lengths SL offset by 5 data points between the first point and peak-force point have been determined.
(7) Find the maximum slope. This is the Approximate Maximum Slope (AMS).
(8) Using the Approximate Maximum Slope find Approximate 2% Offset Yield Point by taking a line parallel to AMS at a 2% Offset and finding the point (L_o, El_o) at which this parallel line intercepts the curve.

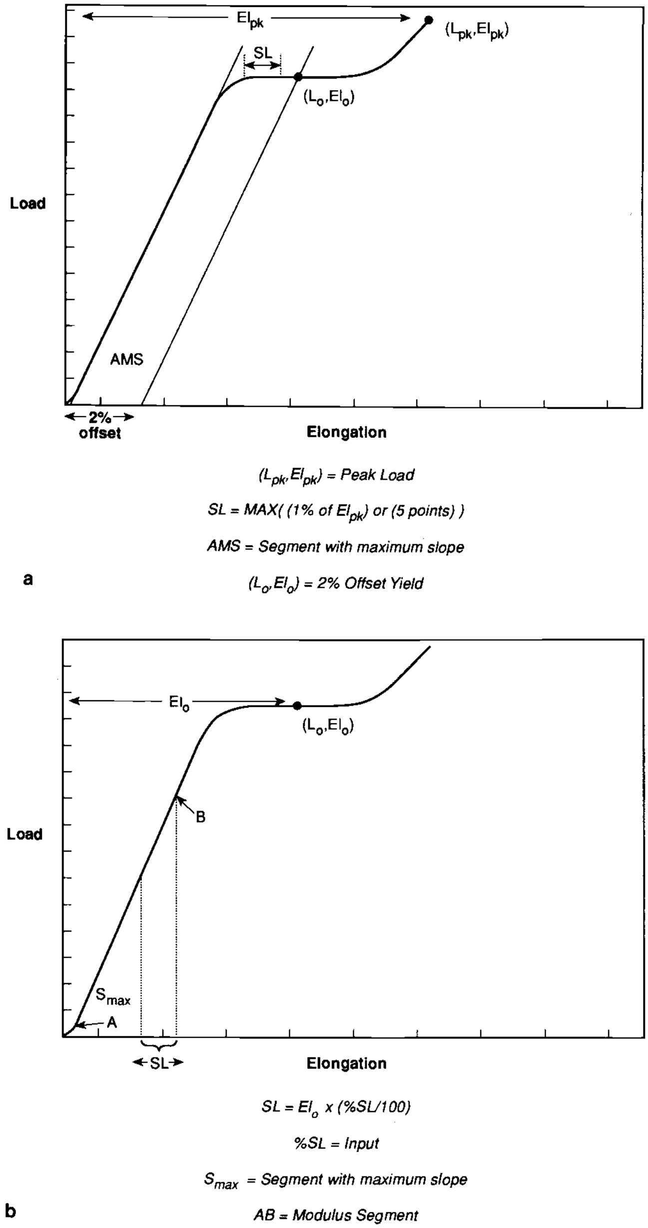


FIG. 4—*Young's Modulus Method* (a) *Step 1*, (b) *Step 2*.

Step 2: Determine the Maximum Slope (Fig. 4*b*)

(1) Define Segment Length $SL = EL_o \times (\%\text{SL}/100)$ where $\%\ SL$ is the prespecified input % Segment Length.
(2) Beginning at the Starting Point find the first segment of length SL or 5 data points, whichever is longer.

(3) Find the slope of this segment.
(4) Find the next segment of length SL or 5 data points, whichever is longer, by moving over one data point and find the slope of this segment.
(5) Repeat this process till the slope of all segments of length SL and offset by one data point from the Starting Point to the Ending Point have been determined.
(6) Find the Segment S_{max} with the maximum slope.
(7) Add one data point to the top of segment S_{max} with the maximum slope and compute the slope of this new segment. If the new slope is within $\%T$ percentage (prespecified input) of the slope of S_{max} then keep the additional point in the segment, and add a new point to the bottom of the segment.
(8) Repeat the process in Step 7 by alternately adding points to the beginning and end of the segment as long as the slope of the resulting segment is within the $\%T$ tolerance of S_{max}.
(9) Make one long segment by combining all the data points found in Step 8, including S_{max}.
(10) Compute the slope of this segment as the Maximum Slope.

Break Point

Several different techniques for determining the break point are used in various ASTM test procedures. The most common one however describes break as the sudden drop in load. The %Drop/Elongation method described in the following algorithm attempts to define break as the change in the slope of the stress-strain curve. This algorithm is recommended for most rigid and semi-rigid materials. It requires the determination of the first point on the force-elongation curve after which the force drops by a specified percent over a specified elongation.

Input Parameters

The following parameters must be specified and explicitly reported when this algorithm is used:

(a) % Drop: In units of percent. Typical suggested value of 40%.
(b) ΔEl (Δ elongation): In units of millimeters (or inches). Typical suggested value of 1.25 mm.

Algorithm (Fig. 5)

(1) Start from the peak force point. The force and elongation at this point are (L_1, El_1).
(2) Find the next point (L_2, El_2) where $El_2 > El_1 + \Delta El$
(3) If $L_2 < L_1 \times (1 - \%\ \text{Drop}/100)$ then Break Point $= (L_1, El_1)$

Else Set (L_1, El_1) = next point on force-elongation curve and repeat Steps 2 and 3 till the break point is found.

If the condition specified in Step 3 is not met over the force-Elongation curve beyond the peak point, then the break point does not exist using the input criteria stated. Under these circumstances it may be necessary either to use a different break point algorithm, or to relax the input criteria.

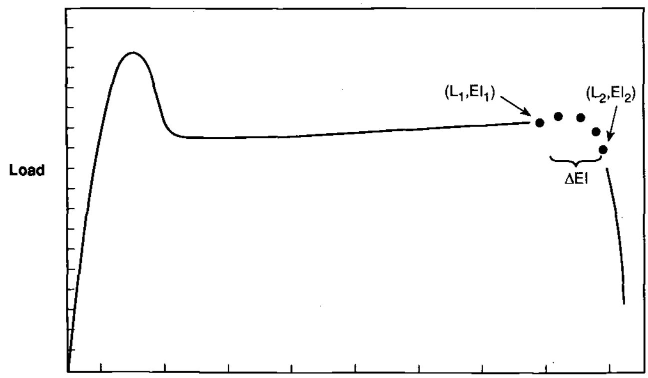


FIG. 5—*Break using %drop/elongation method.*

Yield Point

By most definitions the yield point is the first point at which the stress-strain curve becomes "flat." Since the "flatness" of a curve is a relative term, it is appropriate to relate it to some other measure of how rapidly the stress-strain curve was increasing before yield. This algorithm uses the angle of the stress-strain curve as a measure of flatness. Since the angle will change depending on the scales used, the algorithm uses normalized scales for the x- and y-axis.

Input Criteria

The following criteria must be specified and explicitly reported when this algorithm is used:

(a) Angle (A) expressed in degrees measured from the x-axis. Typical suggested value of 0.5°.
(b) % Segment Length (% *SL*) expressed in units of percent. Typical value of 5% or 5 data points, whichever is longer.

*Algorithm (Figs. 6*a *and* b*)*

This algorithm determines the point on the stress-strain curve where the slope of the stress-strain curve becomes zero on a normalized scale. The scales are normalized such that angle of Peak Force at Peak Extension is 45°, i.e., on graph paper Peak Force would be the same distance on the y-axis as Peak Extension is on the x-axis.

(1) Determine the angle normalization factor a as follows

$$a = El_{max}/L_{pk}$$

where

El_{max} = maximum extension, and

L_{pk} = peak force

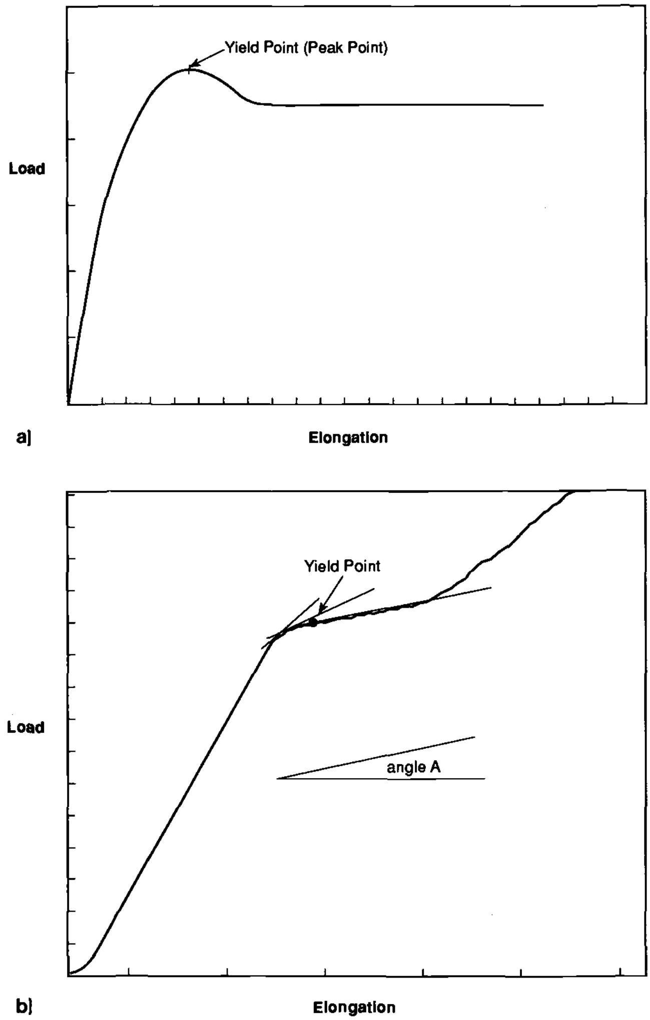


FIG. 6—(a) *Curve with distinct yield,* (b) *yield via slope angle.*

Thus

$$a \times L_{pk}/El_{max} = 1 \text{ so } \arctan(a \times L_{pk}/El_{max}) = 45°,$$

and the scale would be normalized if each force value is multiplied by a.

(2) Define Segment Length SL = MAX{($SL\%$ of EL_{pk}) or (5 data points)} where EL_{pk} is the extension at peak force.

(3) Starting from the last data point used to determine the modulus line, find all the segments of length SL offset by 2 data points. For example, if the first segment of length SL consists of points 1 through 20, then the second segment would be 3 through 22, the third would be 5 through 24, and so on.

(4) Compute the slope of each of these segments up to one segment past the peakforce point. For example, if the peak force is at point 323, then the last segment will be the one which begins at 324.

(5) Starting from the first segment determine if any segment has a negative slope (Fig. 6*a*). If this is true then the yield point is the point of peak force from the start up to and inclusive of all the data points in the first segment with negative slope. The algorithm is complete.
(6) If there is no segment with negative slope (Fig. 6*b*) then find the "point of inflection" yield point instead. Compute the normalized angle of each segment as follows

$$A = \arctan (a \times m)$$

where

a = normalizing factor previously calculated, and

m = slope of the segment.

(7) Beginning at the start of the curve, find the first segment whose normalized angle A_n is less than or equal to A degrees (specified input).
(8) If such a segment exists then the first point in this segment is the yield point.
(9) If such a segment does not exist then the first peak force point is the yield point.

Proportional Limit Point

The Proportional Limit Point is defined as the first point on the stress-strain curve where the curve deviates from straight-line behavior (see ASTM D 638, etc.). For practical purposes, the deviation from straight line is defined as a change in the angle of the stress-strain curve as compared to the angle of the Young's Modulus line.

Input Criteria

The following criteria must be specified and explicitly reported when this algorithm is used:

(a) % Tolerance (%T) expressed as a percent drop from the angle of the modulus line.
(b) % Segment Length (%SL). In units of percent. Typical value of 5% or 5 data points, whichever is longer, but may vary with the material.

Algorithm (Fig. 7)

The algorithm determines the point on the stress-strain curve where the angle of the stress-strain curve changes from the angle of the modulus line by a certain percentage. Like the algorithm for Yield Point, the scales are normalized such that angle of Peak Force at Peak Extension is 45°, i.e., on graph paper Peak Force would be the same distance on the y-axis as Peak Extension is on the x-axis.

(1) Determine the angle normalization factor a as follows

$$a = El_{max}/L_{pk}$$

where

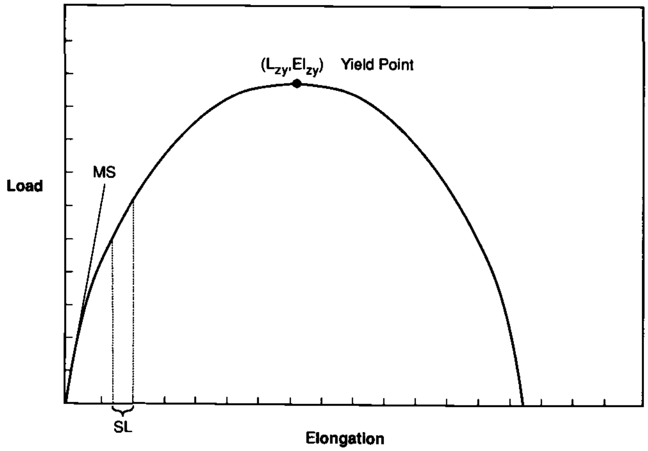
El_{max} = maximum extension, and

L_{pk} = peak force.

Thus

$$a \times L_{pk}/El_{max} = 1$$

so $\arctan (a \times L_{pk}/El_{max}) = 45°$, and the scale would be normalized if each force value is multiplied by a.



MS = Maximum Slope from Modulus Calculation

SL = Segment Length

FIG. 7—*Proportional limit.*

(2) Determine the Yield Point (L_y, E_y) using the algorithm described in the section on Yield Point.
(3) Define Segment Length SL = MAX{($SL\%$ of E_y) or (5 data points)}.
(4) Starting from the last data point used to determine the modulus line, find all the segments of length SL offset by 2 data points. For example, if the first segment of length SL consists of points 41 through 60, then the second segment would be 43 through 62, the third would be 45 through 64, and so on.
(5) Compute the slope of each of these segments up to one segment past the yield. For example, if yield is at point 323, then the last segment will be the one that begins at 324.
(6) Compute the normalized angle of each segment as follows

$$A_n = \arctan (a \times m)$$

where

a = normalizing factor calculated as shown, and

m = slope of the segment

Also, the reference angle A_r which is the normalized angle of the modulus line

$$A_r = \arctan (a \times M)$$

where

a = normalizing factor calculated as shown, and

M = slope modulus line.

(7) Beginning at the start of the curve, try to find the first segment whose normalized angle A_n is less than or equal to A_r by $\%T$ percent, i.e.,

$$A_n < A_r \times (100 - \%T)/100$$

(8) If such a segment exists, then the first point in this segment is the Proportional Limit Point.

Conclusion

An important goal of testing is to produce information that is consistent and reproducible. The algorithms used to analyze stress-strain curves are as important for testing as the calibration of transducers, specimen preparation and conditioning, gripping, and other areas that are well covered in ASTM and other standard procedures. The algorithms described in this paper have been used successfully in several commercial software packages for the data interpretation of mechanical test results for a variety of different materials. They provide a flexible means of tailoring the software to produce test results that are repeatable and are consistent with the judgment of skilled users. Furthermore, if the inputs to the algorithms are reported along with the stress-strain data, the results can be recomputed by anyone without ambiguity. To improve the quality and consistency of mechanical testing data, it is important for ASTM and other standards organizations to develop standard algorithms. Otherwise, test results will continue to be subject to variations due to the use of different algorithms, regardless of how accurate the testing system may be.

Acknowledgments

The author wishes to acknowledge Doug Albert of SINTECH Division of MTS Systems Corp. and Janet Locke of Instron Corp. for their assistance in refining the algorithms described in this paper and as developed for ASTM Subcommittee D20.25 on Data Acquisition and Interpretation.

D. K. Scherrer[1]

A Comparison of Automated Versus Manual Measurement of Total Elongation-Tension Testing

REFERENCE: Scherrer, D. K., "**A Comparison of Automated Versus Manual Measurement of Total Elongation-Tension Testing,**" *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 65–74.

ABSTRACT: A study was conducted to compare two methods of determining the total percent elongation from standard tension tests. For each test, total percent elongation was measured by two methods: the conventional manually "measured" method where the broken specimen halves are fitted back together after the test, and the automated "extensometer" method where elongation to fracture is determined by an extensometer that is left on the specimen up to the moment of fracture.

Comparison of "measured" and "extensometer" elongation results reveals excellent agreement between the two methods. The difference between the two elongation values is generally less than 1% elongation, with the measured value normally being higher.

A model was developed that could be used to predict the "measured" elongation from the "extensometer" elongation to within 1% to 1.5% of the actual "measured" value.

KEYWORDS: uniaxial tension tests, mechanical properties, total percent elongation, automated tension tests, variability

The uniaxial tension test is widely used to provide basic design information on the strength and ductility of materials, but more commonly as an acceptance test for specification of materials. With today's emphasis on stricter quality control, there is an increased demand on materials manufacturers to more stringently test their material to assure property uniformity. For this reason, automated testing equipment is quickly becoming an industry standard as the need for reduced testing costs and quick turnaround time continues to be of prime importance.

One time-consuming aspect of the uniaxial tension test is the manual method for determining total percent elongation to fracture. This parameter is considered an important property of the tension test, as it is a strong indicator of a material's formability. However, determination of total elongation can easily be accomplished with an automated testing system at a reduced testing cost.

Test Procedure and Equipment

All tests for this study were conducted on a 5000 lbf (22 kN) capacity, computer-controlled, Horizontal Tinius Olsen testing machine. This is a four-quadrant drive system with a ball screw drive and crosshead position control. The computer system controls both the machine

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operation and the data acquisition. The data acquisition rate is approximately 5 data pairs per second.

The machine is equipped with a horizontal extensometer that automatically pivots down onto the test specimen at the start of the test. The extensometer is designed to remain in contact with the specimen up to the moment of fracture. The extensometer is verified in accordance with ASTM Method of Verification and Classification of Extensometers (E 83) and meets Class B-2 to 2% strain and Class C from 2% to 50% strain.

All specimens were tested in accordance with ASTM Test Methods of Tension Testing of Metallic Materials (E 8). The specimens were machined with a 2¼-in. (57.2-mm) reduced parallel section, 0.500 in. (12.7 mm) wide (see Fig. 1 of ASTM E 8-90a). Strain rates, based on a free running crosshead speed, were 0.05 strain/min up to 3% strain and then increased to 0.4 strain/min to fracture.

Methods of Determining Total Percent Elongation

For each test, total percent elongation was determined by two methods.

Method 1—Manually "Measured"

Prior to testing, 2-in. (50.4-mm) gage marks were centered in the reduced parallel section using a diamond indenter. Following complete separation of the specimen at fracture, the two pieces were fitted back together with the specimen aligned parallel along the same plane. The final distance between gage marks was determined and used to calculate percent elongation.

The final length was measured using a dedicated (dimensional) specimen measuring device that is directly interfaced to the computer system. This means that the operator is required to align the broken specimen halves and manually adjust the gage readout over the gage marks, but the actual measurement inputs were automatic. The specimen measuring unit was verified before and after the time period for which data are reported and was found to be accurate to within 0.001 in. (0.0254 mm) over the range of percent elongation reported.

Method 2—Automatic "Extensometer"

This method involved using the built-in extensometer. This unit is designed to remain on the specimen up to the moment a specified percent drop in stress is achieved just prior to complete fracture. For the reported "extensometer" total elongation values, the unit was set up to stop data acquisition at 15% of the maximum stress value. The reported strain value was determined from the digitized strain data where total elongation was arbitrarily defined as the strain taken 6 points in front of (before) the first occurrence of a stress/strain point less than 15% of maximum stress (Fig. 1). This strain value point is, of course, somewhat dependent upon strain rate and data acquisition rate; however, both were held constant for all reported results. Total elongation is then determined by subtracting the initial strain at the zero slope intercept point, determined from the initial slope of the stress-strain curve, from the final strain value. No attempt was made to correct for the elastic recovery of the material.

Discussion and Results

Two sets of data were included in this study. The first set consisted of select drawing quality, low-carbon sheet steels having elongation values ranging from 37% to 48%. These

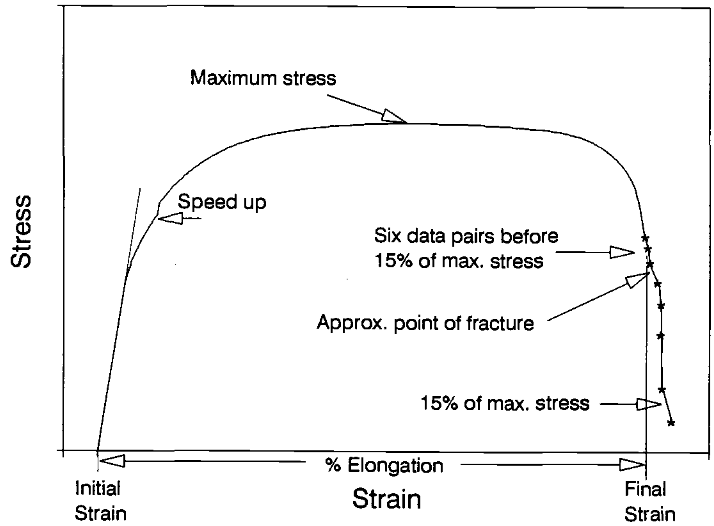

FIG. 1—*Stress-strain plot showing automatic "extensometer" method for determination of total percent elongation.*

included Class 1 and Class 2, Deep Drawing Quality Special Killed (DDQSK) and Drawing Quality Special Killed (DQSK) grade cold-rolled and coated (electrogalvanized and hot dipped galvanized for automotive outer body parts) sheet. The samples were randomly selected from data which were collected over a six month period for which corresponding longitudinal and transverse tensile coupons had been tested. Thickness ranged from 0.027 in. (0.69 mm) to 0.06 in. (1.52 mm). No attempt was made to separate data according to specific grade or class. A total of 1149 individual tests were included. These data were further separated to see if test direction relative to the primary rolling direction had an effect. There were 575 tests that were sampled with the specimens oriented longitudinally and 574 corresponding specimens oriented transverse to the sheet rolling direction.

Group 1—Low-Carbon Drawing Quality Steel, Class 1 and Class 2

A comparison of extensometer elongation (E_{ext}) versus measured elongation (E_{meas}) for the 1149 individual specimens is shown in Fig. 2. Also included is the one-to-one correspondence and the best fit line for the sample population. The sample means and variability parameters are provided in Table 1. Analysis shows that there is a statistically significant difference between the means (E_{meas} mean = 43.6% and the E_{ext} mean = 43.2%). However, this difference is slight (0.4% elongation offset) and, for all practical purposes, the best fit line exhibits a one-to-one slope.

Further examination shows there is no significant difference between the sample population variation of the two elongation methods (E_{meas} Variance = 3.54 and E_{ext} Variance = 3.25).

A histogram for the elongation differences ($E_{meas} - E_{ext}$) of the individual points (Fig. 3) shows a normal distribution pattern for this sample population and 95% (+/− 2 σ) of the individual differences lie within +/−1% elongation of the mean difference.

The best fit line model may also be used to predict the E_{meas} for a specific E_{ext} elongation value. The analysis of variance for the linear regression (Table 1*b*) indicates that the linear

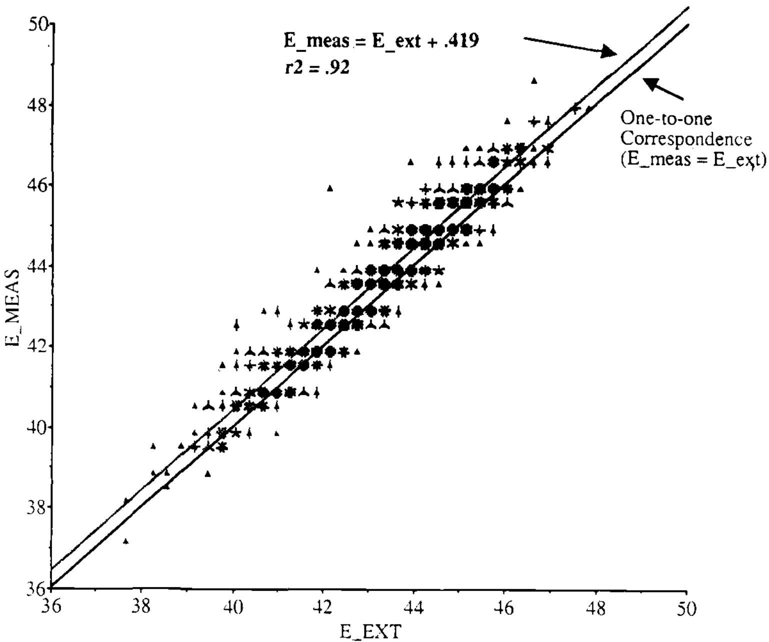

FIG. 2—*Comparison of "measured" elongation to "extensometer" elongation for Group 1, 1149 low-carbon drawing quality steel specimens. (Note: Approximately 1000 observations are hidden; number of lobes for each plot point reflects number of observations.)*

equation, $E_{meas} = 1.001 \times E_{ext} + 0.419$, can be used effectively to predict E_{meas} from the E_{ext} value since it provides a good model (P-value < 0.001) with a low level of uncertainty (R squared $= 0.92$, which says 92% of variability can be explained by E_{ext}). Further analysis shows that from a future single E_{ext} value, the model can predict E_{meas} within $+/-1.0\%$ of the actual measured elongation, based on a prediction interval having a 95% confidence level.

Group 1—Comparison of Longitudinal and Transverse Specimen Orientation Relative to Sheet Rolling Direction

The sample population was made of subgroups that included duplicate longitudinal and transverse specimens taken from each sheet of material included in the sample population. Therefore, the sample group could be further broken down to compare the longitudinal tension tests to the transverse tension tests. Analysis of these data (Table 2) demonstrates that as expected, there is a statistically significant difference between the mean longitudinal (43.8%) and the mean transverse (43.0%) elongations. However, the data do not suggest that a difference exists between the mean difference ($E_{meas} - E_{ext}$) for longitudinal and transverse specimens. Therefore, the same model may be applied to predict E_{meas} regardless of test specimen orientation.

Group 2—General Steel Category Including Low-Carbon and Stainless (Ferritic and Austenitic) Steels

The second set of data was randomly selected to encompass a much wider variety of steels with elongations ranging from 1% to 48%. This sample population included low-carbon

TABLE 1—*Statistical analysis of Group 1, low-carbon drawing quality steels.*

(a) *Comparison of Variation.*

Variable	Count	Mean	Std. Dev.	Std. Error	Minimum	Maximum	Range	Variance	Coef. of Var.	Sum	Sum of Sqr.
$X1$: E_{meas}	1149	43.64	1.881	0.055	37.00	48.5	11.5	3.536	4.309	50 141.5	2 192 197.25
$X2$: E_{ext}	1149	43.19	1.802	0.053	37.60	47.7	10.1	3.248	4.173	49 623.7	2 146 907.33
$X3$: E_{diff}	1149	0.451	0.532	0.016	−1	3.8	4.8	0.283	118.055	517.8	558.28

(b) *Simple Regression Analysis $X1$:E_{ext} $Y1$:E_{meas}*

ANALYSIS OF VARIANCE TABLE

Count	R	R-squared	Adj. R-squared	RMS Residual
1149	0.959	0.92	0.92	0.532

Source	DF	Sum Squares	Mean Square	F-test
Regression	1	3734.79	3734.79	13 183.776
Residual	1147	324.93	0.283	p = 0.0001
Total	1148	4059.72	—	—

BETA COEFFICIENT TABLE—PARAMETER ESTIMATES

Variable	Coefficient	Std. Err.	Std. Coeff.	t-Value	Probability
Intercept	0.419	—	—	—	—
Slope	1.001	0.009	0.959	114.821	0.0001

Best fit line: $E_{meas} = 1.001 \times E_{ext} + 0.419$

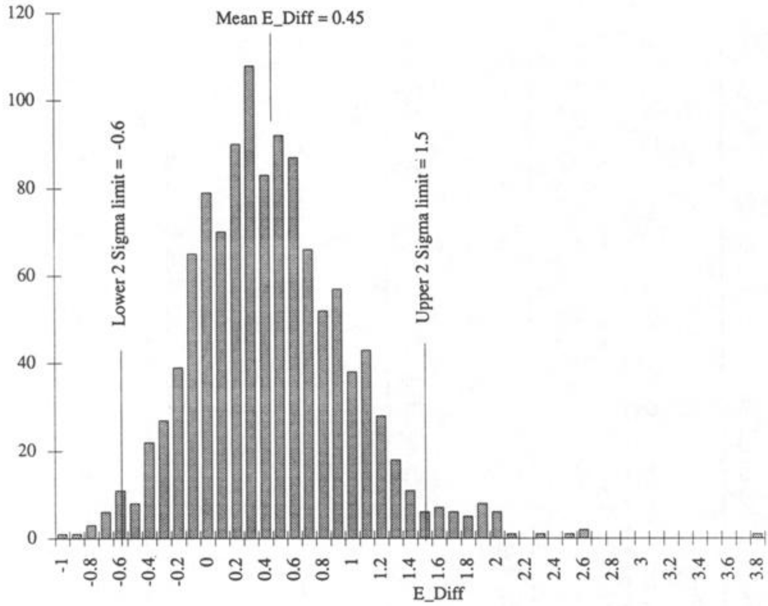

FIG. 3—*Distribution plot for elongation differences (E_{meas} − E_{ext}) for Group 1, 1149 low-carbon drawing quality steel specimens.*

drawing quality and low-carbon high strength steels, as well as some ferritic and austenitic stainless steels. Thicknesses ranged from 0.015 in. (0.38 mm) to 0.10 in. (2.54 mm). This group was randomly taken from tests that were conducted over a several month period and consisted of 689 individual tests. A histogram of E_{meas} (Fig. 4) is included to better illustrate the overall elongation distribution of the sample population.

A comparison of E_{ext} versus E_{meas} for the 689 individual specimens along with the one-to-one correspondence and best fit line is shown in Fig. 5. The sample means and variability parameters are provided in Table 3. Analysis again shows a statistically significant difference between the means (E_{meas} mean = 30.5% and E_{ext} mean = 29.8%) and, the mean difference (0.7) is only slightly greater than for the first group. This is not surprising since this sample population included a much larger elongation range and variety of materials than the first sample group.

Although no statistically significant difference is found between the variation of the two methods, a slightly lower degree of variation occurred with the E_{ext} method.

A histogram of the elongation differences for the individual tests is provided in Fig. 6. Included is the sample population mean difference along with the 2 Sigma limits which indicates that 95% of the entire sample population difference lies within +/−1.5% elongation of the mean difference.

Examination of the simple regression analysis results (Table 3*b*) shows that the best fit line provides a good model (*P*-value < 0.001) with a very low level of uncertainty (*R*-squared = 0.99). Statistical analysis shows that from a future single E_{ext} value, the model ($E_{meas} = 1.031 \times E_{ext} - 0.244$) can predict E_{meas} within +/−1.4% of the actual measured elongation, based on a prediction interval having a 95% confidence level.

TABLE 2—*Comparison of "measured" elongation (E_{meas}) to "extensometer" elongation (E_{ext}). Effect of test specimen orientation relative to sheet rolling direction for Group 1, low-carbon drawing quality steels.*

								T-test			
Variable	Dir.	Count	Mean	Std. Dev.	Std. Error	Minimum	Maximum	Variances	T	DF	Prob > $\|T\|$
E_{meas}	Long.	575	44.02	1.770	0.0738	39.5	48.0	Unequal	7.0948	1140	0.0001
	Trans.	574	43.25	1.910	0.0797	37.0	48.5	Equal	7.0953	1147	0.0001
For HO: Variances are equal, $F' = 1.17$ with 573 and 574 DF Prob > $F' = 0.0671$.											
E_{ext}	Long.	575	43.60	1.682	0.0701	39.6	47.5	Unequal	7.9257	1138.9	0.0001
	Trans.	574	42.78	1.827	0.0763	37.6	47.7	Equal	7.9262	1147.0	0.0001
For HO: Variances are equal, $F' = 1.18$ with 573 and 574 DF Prob > $F' = 0.0474$.											
E_{diff}	Long.	575	0.426	0.511	0.0213	−0.9	2.6	Unequal	−1.6008	1140.2	0.1097
($E_{meas} - E_{ext}$)	Trans.	574	0.476	0.551	0.0230	−1.0	3.8	Equal	−1.6009	1147.0	0.1097
For HO: Variances are equal, $F' = 1.16$ with 573 and 574 DF Prob > $F' = 0.0705$.											

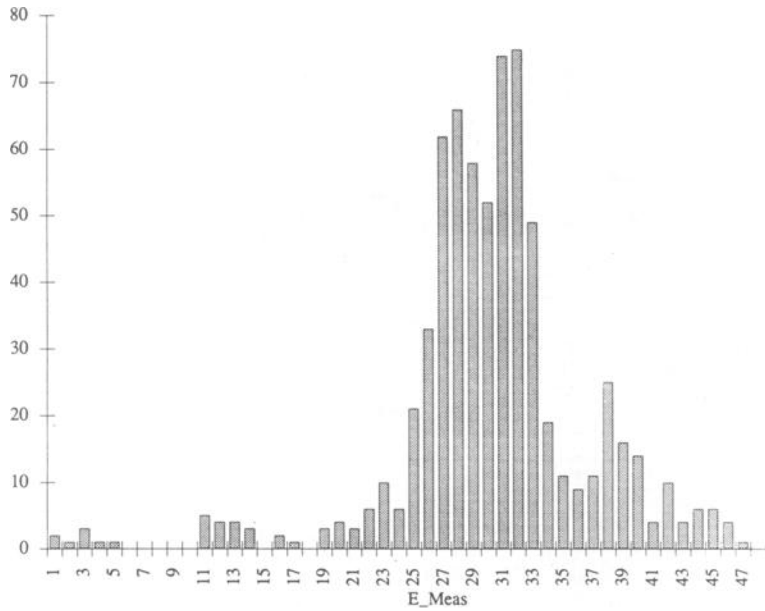

FIG. 4—*Distribution plot for elongation "measured" for Group 2, general steel category including low-carbon and stainless steels, 689 specimens.*

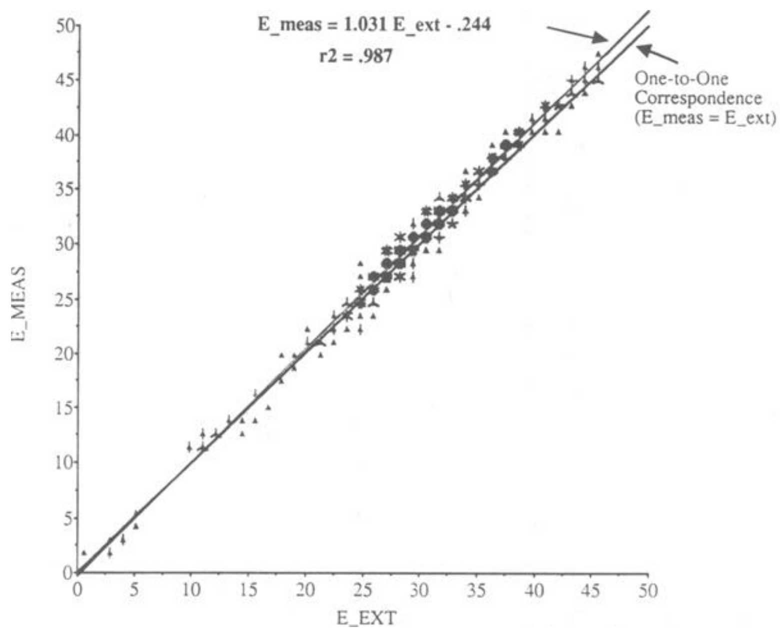

FIG. 5—*Comparison of "measured" elongation to "extensometer" elongation for Group 2, general steel category including low-carbon and stainless steels, 689 specimens. (Note: Approximately 590 observations are hidden; number of lobes for each plot point reflects number of observations.)*

TABLE 3—*Statistical analysis of Group 2, general steel category including low-carbon and stainless steels.*

(a) *Comparison of Variation.*

Variable	Count	Mean	Std. Dev.	Std. Error	Minimum	Maximum	Range	Variance	Coef. of Var.	Sum	Sum of Sqr.
$X1$: E_{meas}	689	30.48	6.43	0.245	1.5	47.5	46	41.349	21.094	21 003.5	668 719.25
$X2$: E_{ext}	689	29.81	6.197	0.236	1	45.9	44.9	38.404	20.79	20 538	638 627.16
$X3$: E_{diff}	689	0.676	0.759	0.029	−2.6	2.9	5.5	0.575	112.28	465.5	710.41

(b) *Simple Regression Analysis $X1$:E_{ext} $Y1$:E_{meas}.*

ANALYSIS OF VARIANCE TABLE

Count	R	R-squared	Adj. R-squared	RMS Residual
689	0.993	0.987	0.987	0.735

Source	DF	Sum Squares	Mean Square	F-test
Regression	1	28 077.055	28 077.055	52 024.018
Residual	687	370.77	0.540	$p = 0.0001$
Total	688	28 447.824		

BETA COEFFICIENT TABLE—PARAMETER ESTIMATES

Variable	Coefficient	Std. Err.	Std. Coeff.	t-Value	Probability
Intercept	−0.244	—	—	—	—
Slope	1.031	0.005	0.993	228.088	0.0001

Best fit line: $E_{meas} = 1.031 \times E_{ext} - 0.244$

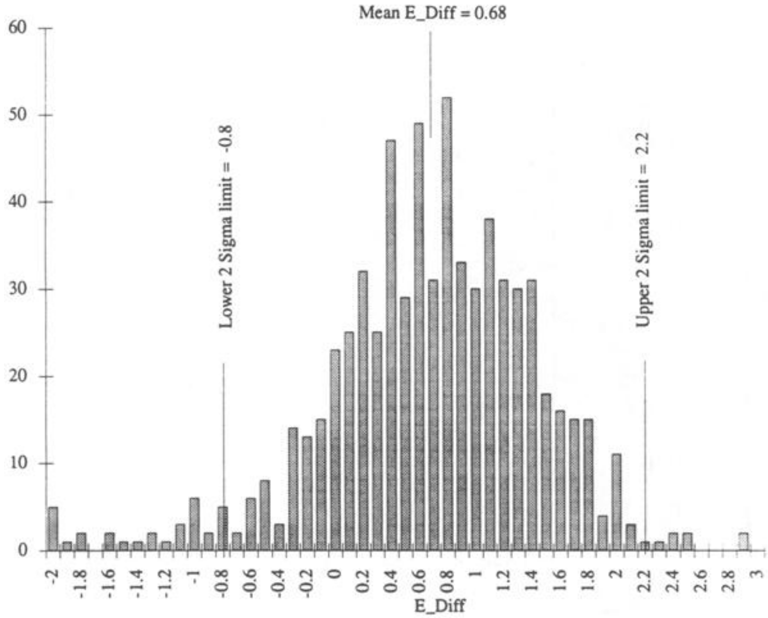

FIG. 6—*Distribution plot for elongation differences* ($E_{meas} - E_{ext}$) *for Group 2, general steel category including low-carbon and stainless steels, 689 specimens.*

Conclusion

Comparison of "measured" and "extensometer" elongations reveals excellent agreement. The difference, although found to be statistically significant, is generally less than 1% elongation, with the measured value normally being higher. It is possible that with further study, the "extensometer" method can be modified (e.g., the number of data pairs to look back from the data acquisition stop point, the defined stop point [% of max. stress] and correction for elastic recovery) and this difference could be further minimized.

Although not statistically significant, the "extensometer" elongations exhibited slightly less variation than the "measured" elongations.

The best fit linear regressions can be effectively used to predict the "measured" elongation value from the "extensometer" value within 1 to 1.5% of the actual "measured" value.

Acknowledgment

The author wishes to acknowledge Krista Goble, Statistician, for her assistance in the statistical analysis and evaluation of the data presented in this report.

Joel J. Young[1]

A Technique for Determining Yield Point Elongation

REFERENCE: Young, J. J., **"A Technique for Determining Yield Point Elongation,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 75–90.

ABSTRACT: A method capable of calculating the Yield Point Elongation (YPE) in an automated testing system was investigated and an algorithm for determining YPE was developed. One problem that had to be resolved before a YPE algorithm could be developed was that the definition of YPE as presented in ASTM E 6, Definitions of Terms Relating to Methods of Mechanical Testing, was based upon an informal definition of discontinuous yielding. Automation of the YPE calculation required a formal definition. Discontinuous yielding was formalized to be the region over which the stress-strain diagram exhibited points of inflection (i.e., points where the second derivative of the stress-strain diagram is equal to zero). The definition of YPE then became "the difference between the elongation at the yield point and the last inflection point."

Given the formalized definition of discontinuous yielding, it became necessary to develop an algorithm for the calculation of first and second derivatives. This investigation centered on the use of difference equations and the use of third order polynomial approximations (cubic splines) to the sampled data. Since derivative calculations inherently increase any noise that is present in the system, the susceptibility of each of these algorithms to noise was examined by impressing a gaussian noise source onto a sinusoid. The cubic spline method was selected since it caused the least amount of noise amplification. The amount of noise rejected by the cubic spline increased with the size of the region that was fitted. However, this caused an increase in the error of the polynomial approximation. When applied to actual test data, the error in the polynomial approximation resulted in increased error in the location of the inflection points. This put a limit on the amount of noise that could be rejected.

Since the noise could not be completely eliminated, false inflection points were exhibited. Therefore it was necessary to identify and ignore these false inflections. This was accomplished by calculating the slopes at successive inflection points and comparing them to the slope of the line intersecting the origin and the point of ultimate load (i.e., the point at which the maximum load occurred after lower yield). If the slope at the inflection point was within certain bounds, specified as a percentage of the ultimate load line slope, then the inflection point was considered to be valid; otherwise, it was rejected. Once the false inflection points were eliminated, the location of the last inflection was identified and the yield point elongation was calculated.

KEYWORDS: yield point elongation (YPE), yield point, inflection point, cubic spline, discontinuous yielding, parametric equations, ultimate tensile strength

With the increasing use of computers in materials testing it has become necessary to review current manual testing practices and data analysis procedures in terms of their implementation in an automatic testing environment. The purpose of this paper is to examine the issues in performing automated calculation of yield point elongation.

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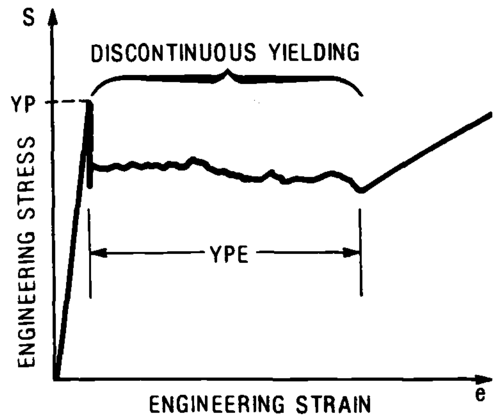


FIG. 1—*Stress-strain diagram for determination of yield point and yield point elongation in a material exhibiting discontinuous yielding. (Reprinted for ASTM Annual Book of Standards, Vol. 3.01, E 6.)*

Yield Point Elongation (YPE)

The definition of YPE as defined by ASTM E 6, Definitions of Terms Relating to Methods of Mechanical Testing, is as follows: "In materials that exhibit a yield point, (YPE is) the difference between the elongation at the completion and at the start of discontinuous yielding." (Figs. 1 and 2.) One problem with this definition is the lack of a rigorous definition of discontinuous yielding. Since there is no precise algorithmic definition, it is left up to the individual to derive the definition from an examination of these figures. This can lead to contradictory definitions of YPE which in turn will cause incompatibility between the algorithms created for determination of YPE. This can lead to discrepancies in testing results between different testing organizations or results obtained by testing machines from various manufacturers. Before a YPE algorithm can be written it is necessary to formally define discontinuous yielding. This definition will be based upon the detection of inflection points; first the concept of an inflection point will be explored, then the definition of discontinuous yielding.

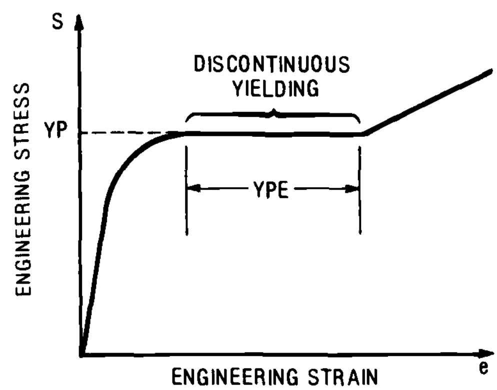


FIG. 2—*Stress-strain diagram for determination of yield point and yield point elongation in a material exhibiting discontinuous yielding. (Reprinted from ASTM Annual Book of Standards, Vol. 3.01, E 6.)*

Inflection Points

An inflection point is a point on a curve where the second derivative changes sign, or where the slope of the curve is a maximum or minimum. In the case of a straight line where the second derivative is constant and equal to zero (i.e., the slope is constant), an inflection point does not exist. Figure 3 shows the load/displacement plot of a material that does not meet the requirements of E6-42 as having a region of discontinuous yielding. It can be seen that the slope of the curve in Fig. 3 is monotonically decreasing [*1*] from the start to the end of the test, with the exception of the speed change point. Since the change in slope is

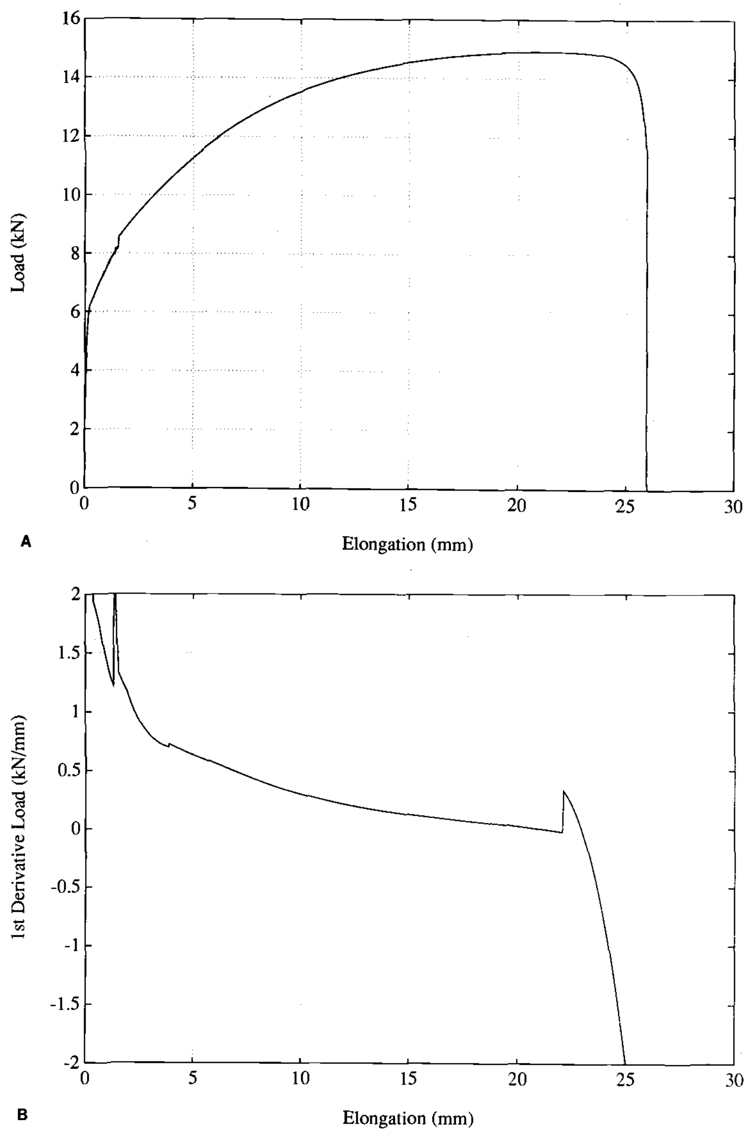


FIG. 3—(a) *Load elongation diagram for a material not exhibiting discontinuous yielding;* (b) *first derivative load-elongation diagram for a material not exhibiting discontinuous yielding.*

monotonic the second derivative never crosses zero, therefore there are no inflection points. In Figs. 1 and 2, the change in slope is not monotonic, so there is at least one point in each curve where the second derivative goes through 0 (e.g., there exists at least one inflection point). Therefore, if a material exhibits discontinuous yielding there must also exist one inflection point. However, this is not yet a sufficient condition. If an inflection point exists, it does not necessarily follow by the definition in ASTM E 6 that discontinuous yielding exists.

Discontinuous Yielding

From Figs. 1 and 2, it is reasonable to assume that the start of discontinuous yielding occurs at the yield point of the material. From this assumption, the material shown in Fig. 4 would not exhibit discontinuous yielding, even though it has two inflection points. If the presence of inflection points was sufficient to indicate the presence of discontinuous yielding, then Fig. 4 would also exhibit discontinuous yielding even though it does not exhibit YPE. Further examination of Figs. 1 and 2 appears to indicate that YPE exists only in those materials in which discontinuous yielding occurs after the yield point. If this requirement is added to the definition of YPE, then the detection of inflection points can be made a necessary and sufficient condition for the detection of discontinuous yielding. The region of discontinuous yielding can now be defined as the region between the first and last inflection points. There is now sufficient information to rigorously define YPE.

Yield Point Elongation—In those materials that exhibit discontinuous yielding after the yield point, YPE is the difference in elongation between the elongation at the yield point and the end of discontinuous yielding.

Even though a material does not have YPE, the presence of discontinuous yielding may still be significant. However, there is currently no definition for this type of characteristic. Since YPE is defined relative to the elongation at yield point, it would seem reasonable to define this characteristic with respect to the elongation at yield strength. This leads to the following proposed definition:

Yield Strength Elongation (YSE)—In those materials that exhibit discontinuous yielding, YSE is the difference in elongation between the elongation at yield strength and the end of discontinuous yielding.

Effect of Noise on Inflection Point Determination

Finding the locations of the inflection points as previously defined requires the calculation of at least the first derivative and optionally the second derivative. If the first derivative is used then the inflection points correspond to those locations at which the slope reaches a minimum or maximum value. However, the process of taking the derivative of experimental data causes the noise inherent in the data to be amplified. In the following experiments, the data was generated via a sinusoid sampled at intervals of $\pi/1000$ over the range 0 to 2π. The data was then impressed with a 0.0025% peak full-scale gaussian noise source (Fig. 5*a*). The first and second derivatives were then calculated using difference equations and cubic splines.

Derivatives by Difference Equations

Figures 5*b* and *c* show the derivatives of the sinusoid calculated via a first order forward difference equation. Even though the original sinusoid appears to be noise free, the amplification brought about by the first derivative is readily apparent. This noise is then amplified further in the second derivative, causing the signal to be indistinguishable. Since

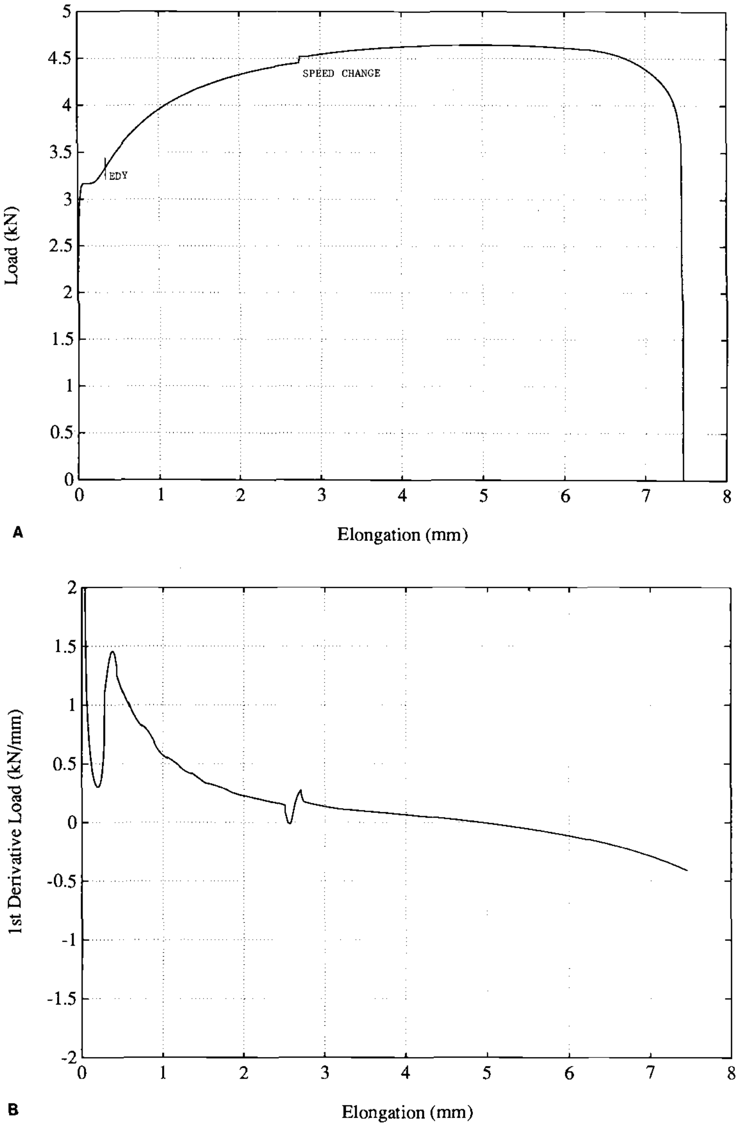
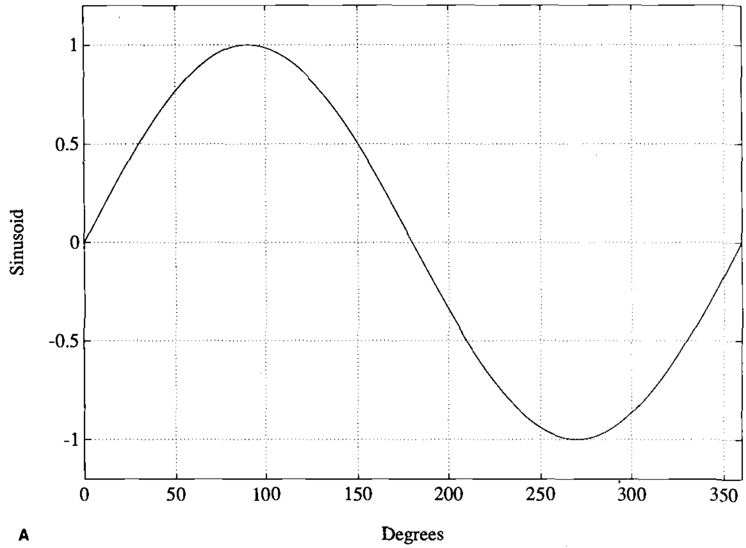
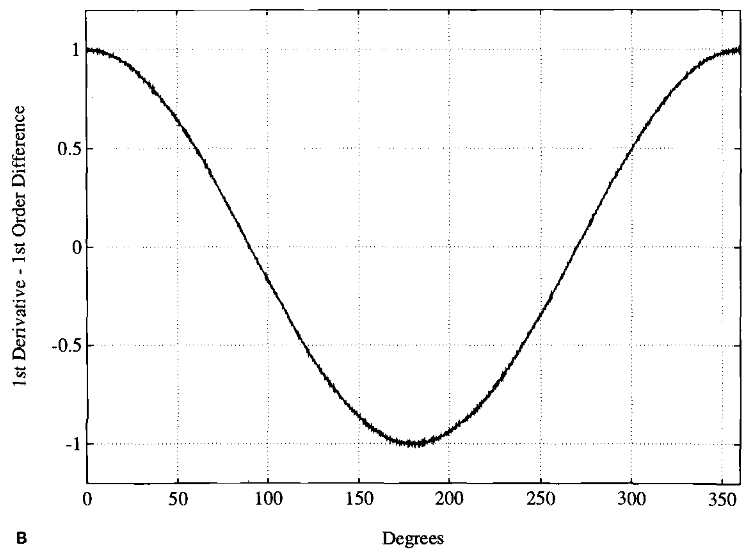


FIG. 4—(a) *Load-elongation diagram for a material not exhibiting discontinuous yielding;* (b) *first derivative load-elongation diagram for a material not exhibiting discontinuous yielding.*

the second derivative has many zero crossings, this method is insufficient for the determination of inflection points. However, if assumptions are made about the overall shape of the waveform, the amount of noise amplification can be reduced by judicious selection of points used in the difference equations. This would be done by specifying the minimum stress or strain intervals, or both, over which the slope would be calculated. Since this effort was directed at determining a general algorithm that was relatively specimen independent, this method was not used.



A

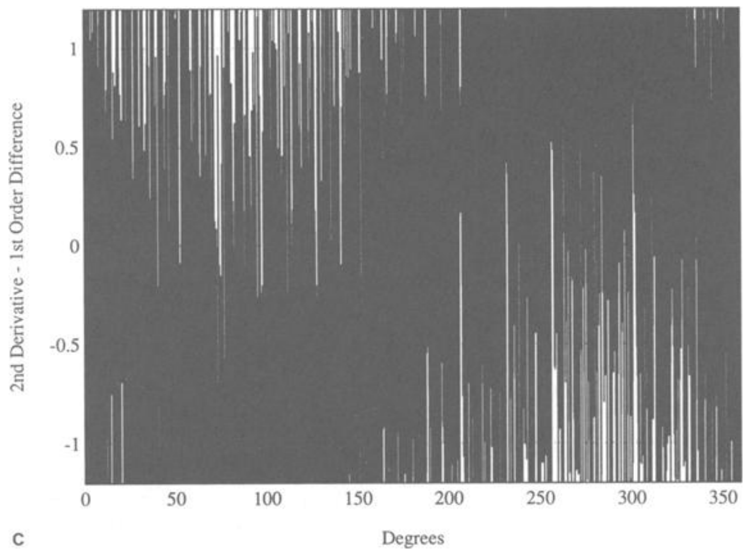


B

FIG. 5—(a) *Sinusoid-degrees with 0.0025% full-scale gaussian noise;* (b) *first derivative of sinusoid using first order forward difference equations;* (c) *second derivative of sinusoid using first order forward difference equations;* (d) *first derivative of sinusoid using cubic spline approximation;* (e) *second derivative of sinusoid using cubic spline approximation.*

Derivatives by Cubic Splines

In calculating derivatives using cubic splines, it is first necessary to determine the third order polynomial that best approximates the experimental data. The experimental data can then be reproduced using this polynomial, resulting in a reduction in the level of noise. The first and second derivatives can also be determined by finding the derivatives of the cubic



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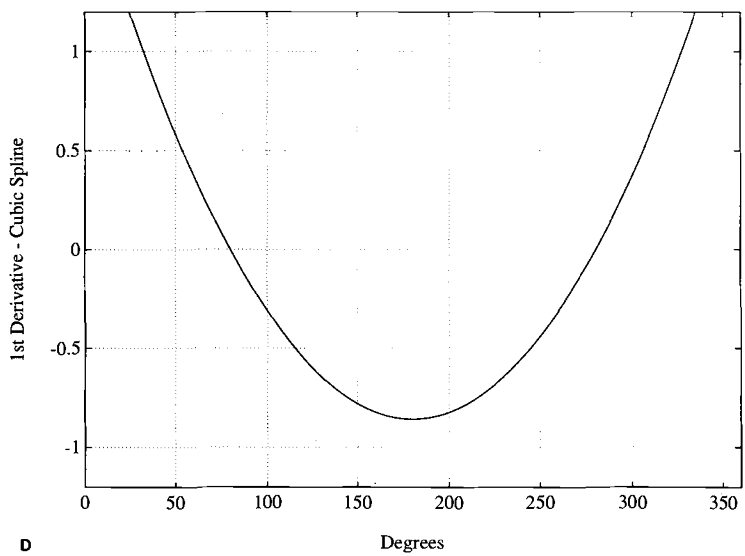
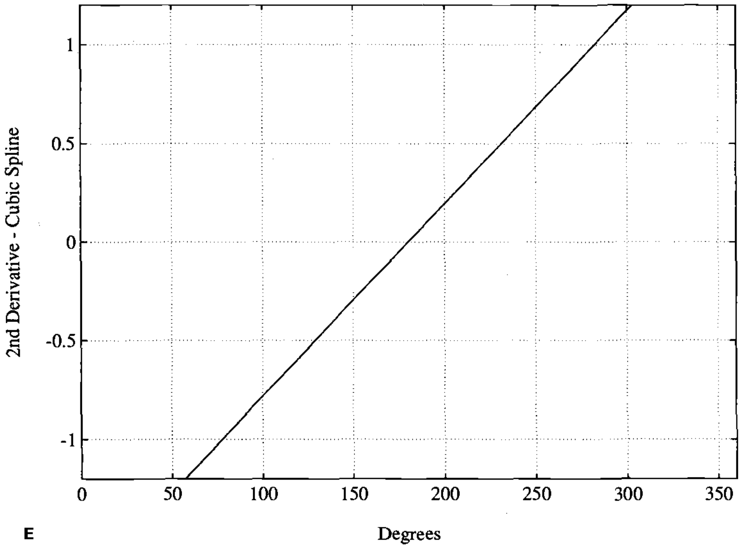


D

FIG. 5—*Continued.*

polynomial. Taking the first derivative of the cubic polynomial will result in a second order polynomial, and the second derivative results in a first order polynomial. Since the second derivative is a first order polynomial, only one inflection point can be found. As seen in Figs. 5*d* and *e*, while the polynomial representations of the derivatives do not give a valid reproduction of the derivatives of the sinusoid, the location of the inflection point is undistorted. Since we are concerned only with the locations of the inflection points and not the shape of the resulting waveform, this method can be used for finding the inflection points.



E

FIG. 5—*Continued.*

Fitting Cubic Splines to Experimental Data

Given an array of data points consisting of pairs (σ,ϵ), a cubic spline is a third order polynomial, $f(\sigma)$, that is used to approximate the relationship between each (σ,ϵ) data pair and is of the form

$$\sigma \approx f(\epsilon) = a_0 + a_1\epsilon + a_2\epsilon^2 + a_3\epsilon^3$$

Since a cubic spline can only contain a single inflection point, it is not sufficient to use a single cubic spline to represent the entire test. This would result in a poor fit of the data and would cause significant errors in the location of the inflection point. In order to provide a good representation of the test, the test data is often divided up into segments and a cubic spline fitted to each individual segment.

Least-Squares Method for Fitting Experimental Data

The method for fitting a cubic spline to experimental data is well-known and will not be described in detail here [*2*], except as applied to the problem at hand. Finding the cubic spline requires the setting up and solving the following matrix equation for $[a_0\ a_1\ a_2\ a_3]$

$$\begin{pmatrix} N & \sum_{i=1}^{N} \epsilon_i & \sum_{i=1}^{N} \epsilon_i^2 & \sum_{i=1}^{N} \epsilon_i^3 \\ \sum_{i=1}^{N} \epsilon_i & \sum_{i=1}^{N} \epsilon_i^2 & \sum_{i=1}^{N} \epsilon_i^3 & \sum_{i=1}^{N} \epsilon_i^4 \\ \sum_{i=1}^{N} \epsilon_i^2 & \sum_{i=1}^{N} \epsilon_i^3 & \sum_{i=1}^{N} \epsilon_i^4 & \sum_{i=1}^{N} \epsilon_i^5 \\ \sum_{i=1}^{N} \epsilon_i^3 & \sum_{i=1}^{N} \epsilon_i^4 & \sum_{i=1}^{N} \epsilon_i^5 & \sum_{i=1}^{N} \epsilon_i^6 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{N} \sigma_i \\ \sum_{i=1}^{N} \epsilon_i\sigma_i \\ \sum_{i=1}^{N} \epsilon_i^2\sigma_i \\ \sum_{i=1}^{N} \epsilon_i^3\sigma_i \end{pmatrix}$$

If the test consists of a large number of data points, this calculation would require a significant number of calculations and would take an inordinate amount of time. Much of this time would be due to calculating and inverting the left-hand matrix. However, if the stress and strain data were fitted separately using parametric equations the amount of processing time required can be reduced.

Simplification Using Parametric Representations for Stress and Strain Data

Fitting each region for stress and strain individually would result in the following pair of equations

$$\sigma \approx f(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

$$\epsilon \approx g(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

In these equations the parametric variable t can take any value as long as its use is consistent within the region over which the cubic fit is performed. If each region is set up such that it contains an odd number of data points, then for a region consisting of points $n_1 \leq n \leq n_2$, if the parametric variable t ranges from

$$-\frac{(t_2 - t_1)}{2} \leq t \leq \frac{(t_2 - t_1)}{2}$$

then the following simplification in the left hand matrix will occur.

$$\begin{pmatrix} N & 0 & \sum_{i=1}^{N} t_i^2 & 0 \\ 0 & \sum_{i=1}^{N} t_i^2 & 0 & \sum_{i=1}^{N} t_i^4 \\ \sum_{i=1}^{N} t_i^2 & 0 & \sum_{i=1}^{N} t_i^4 & 0 \\ 0 & \sum_{i=1}^{N} t_i^4 & 0 & \sum_{i=1}^{N} t_i^6 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{N} \sigma_i \\ \sum_{i=1}^{N} t_i\sigma_i \\ \sum_{i=1}^{N} t_i^2\sigma_i \\ \sum_{i=1}^{N} t_i^3\sigma_i \end{pmatrix}$$

Furthermore, if all of the regions consist of the same number of points, the left-hand matrix and its inverse need to be calculated only once. Finding the coefficients for the polynomial now requires only the calculation of the right-hand matrix and a single matrix multiplication, resulting in a significant reduction in processing time.

Derivatives Using Parametric Representations

Once the parametric representations for stress and strain are determined, the first and second derivatives with respect to time are easily calculated. Given

$$\sigma(t) \approx f(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

$$\epsilon(t) \approx g(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

The first derivative of $\sigma(t)$ and $\epsilon(t)$ with respect to time would be

$$\sigma'(t) = \frac{d\sigma}{dt} = a_1 + 2a_2t + 3a_3t^2$$

$$\epsilon'(t) = \frac{d\epsilon}{dt} = b_1 + 2b_2t + 3b_3t^2$$

The second derivative of $\sigma(t)$ and $\epsilon(t)$ with respect to time would be

$$\sigma''(t) = \frac{d^2\sigma}{dt^2} = 2a_2 + 6a_3t$$

$$\epsilon''(t) = \frac{d^2\epsilon}{dt^2} = 2b_2 + 6b_3t$$

However, it is necessary to find the first and second derivatives of stress with respect to strain. From the chain rule for derivatives, the first derivative would be:

$$\frac{d\sigma}{d\epsilon} = \frac{d\sigma}{dt}\frac{dt}{d\epsilon} = \frac{a_1 + 2a_2t + 3a_3t^2}{b_1 + 2b_2t + 3b_3t^2}$$

The second derivative of stress with respect to strain can be found, by successive application of the derivatives of quotients and the chain rule, to be equal to

$$\frac{d^2\sigma}{d\epsilon^2} = \frac{\frac{d}{dt}\left(\frac{d\sigma}{d\epsilon}\right)}{\frac{d\epsilon}{dt}}$$

$$= \frac{\sigma''(t)\epsilon'(t) - \sigma'(t)\epsilon''(t)}{\epsilon'(t)^2} \cdot \frac{1}{\epsilon'(t)}$$

$$= \frac{\sigma''(t)\epsilon'(t) - \sigma'(t)\epsilon''(t)}{\epsilon'(t)^3}$$

Since second derivative is to be used to find the location of the inflection points, we are only concerned with the points at which the second derivative is equal to zero. This corresponds to finding the values of t such that

$$\sigma''(t)\epsilon'(t) - \sigma'(t)\epsilon''(t) = 0$$

Substituting the equations for the first and second derivatives of $\sigma(t)$ and $\epsilon(t)$ into the above equation yields a quadratic equation. Therefore two inflection points can be found, and are located at

$$t_{1,2} = \frac{-3(a_3b_1 - a_1b_3) \pm \sqrt{9(a_3b_1 - a_1b_3)^2 - 12(a_2b_1 - a_1b_2)(a_3b_2 - a_2b_3)}}{2(a_3b_2 - a_2b_3)}$$

It should be noted that using parametric equations for stress and strain yielded not only computational advantages, but also resulted in a higher order representation for the second derivative.

Determination of YPE

The process of calculating the amount of YPE consists of determining the presence of significant inflection points in the test data and locating where the last significant inflection point occurred. YPE is then calculated by subtracting the elongation at the yield point from the elongation at the last significant inflection point.

Starting Point Determination for Inflection Search

If the search for inflection points started at the end of the test and worked backwards, then the end of discontinuous yielding would correspond to the location of the first significant inflection point that was detected. The starting point was further restricted by setting it to the elongation at Ultimate Tensile Strength (UTS). In this case, UTS refers to the highest load after the lower yield point. In Figs. 6 and 7 it can be seen that the speed change will cause a false inflection point that must be rejected. If a speed change occurred, then the starting point was set to the minimum of the elongation at UTS and the elongation at speed change. This caused both a reduction in algorithm execution time and also eliminated the false inflection due to the speed change.

Dividing the Test into Regions for Cubic Fit

Once the starting point was determined, the test was divided up into regions to be fitted with cubic splines. The number of points (N) to be used to fit each region was determined by dividing the total number of data points acquired during the test by the number of regions to be fitted and then ensuring that the result was an odd number of points. The number of regions specified was varied from 5 to 30. Specifying a small number of regions decreased the sensitivity of the derivatives to noise effects, but increased the error in the fit of the resulting cubic spline. As the number of regions was increased the fit improved, but so did the sensitivity to noise. It was found that dividing the test into 10 to 20 regions provided an acceptable fit while keeping the effect of noise to a reasonable level. It is known that if a curve is divided up into regions and each region fitted separately, the resulting cubic splines will approximate the curve such that the data produced by the cubic splines will be continuous in t, but only piecewise continuous in the derivatives. In order to reduce the discontinuity of the derivatives at the "knots" (e.g., the points at which the cubic splines are joined) each region was chosen such that it overlapped the previous region by $(N\text{-}1)/2$. After a region was fitted, the region over which the cubic spline was considered valid was then reduced by discarding the first and last $(N\text{-}1)/4$ points. Once a region was fitted, the roots of the second derivative of the spline were then determined, resulting in the location of the inflection points *for that polynomial.*

Inflection Point Validation

Since each parametric cubic spline will always have two inflection points, it had to be determined which of these inflection points, if any, were significant. For each region, the inflection points correspond to the locations of the maximum and minimum slopes. Since

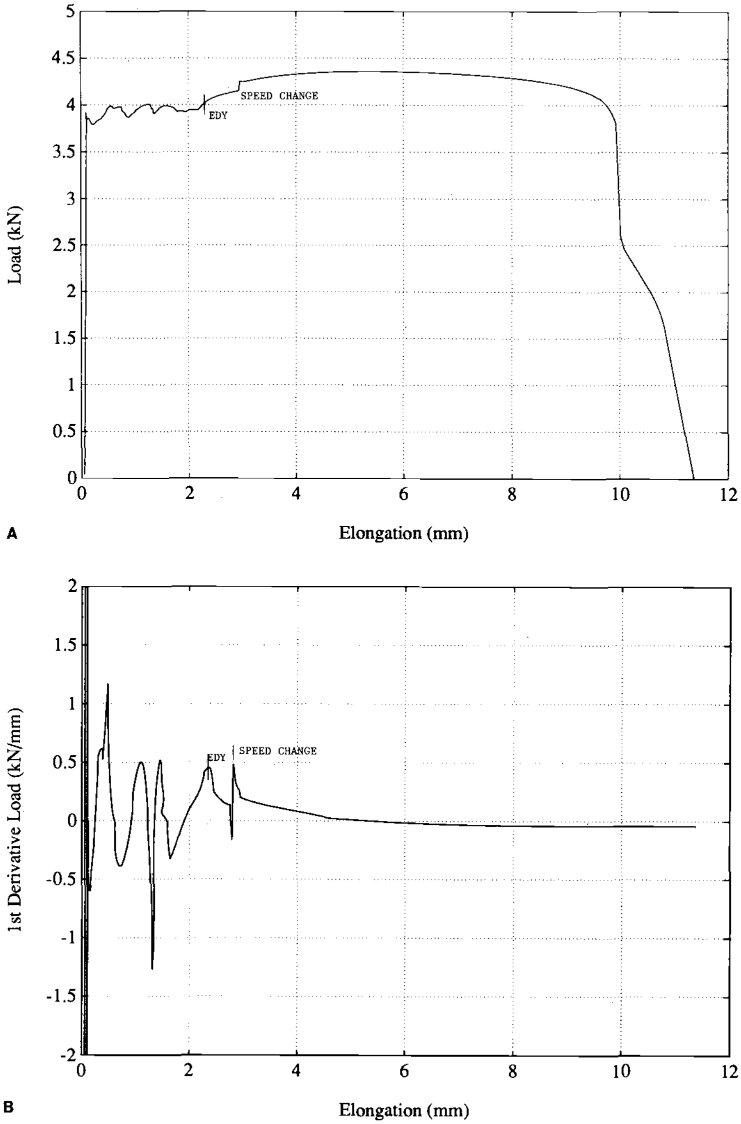
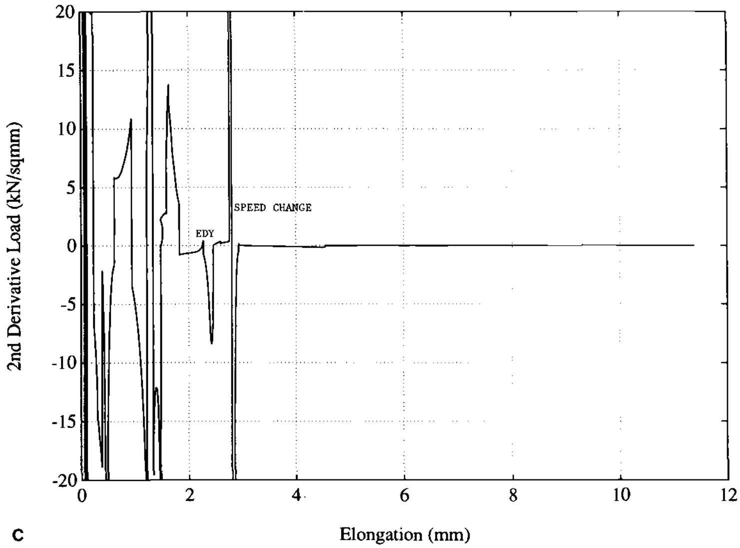


FIG. 6—(a) *Load-elongation diagram for a material exhibiting discontinuous yielding;* (b) *first derivative load-elongation diagram for a material exhibiting discontinuous yielding via piecewise continuous cubic splines;* (c) *second derivative load-elongation diagram for a material exhibiting discontinuous yielding via piecewise continuous cubic splines.*

the inflection point corresponding to the minimum slope cannot be the end of discontinuous yielding, it can be rejected. If the location of the inflection point at which the slope is a maximum was such that it fell outside the valid region of the cubic spline, then is was rejected. If it fell within the valid region, then it became a candidate for the location of the end of discontinuous yielding.



c

FIG. 6—*Continued.*

Due to the effect of noise in the system there will still be some insignificant inflection points detected, as can be seen in Figs. 6*c* and 7*c*, which must be recognized as insignificant and rejected. Note that in Fig. 7*c* the second derivative does not appear to show a zero crossing at end of discontinuous yielding (EDY). This is due to resolution limitations in the data reproduction. This can be confirmed by the location of the maximum slope in Fig. 7*b*. These spurious inflections were eliminated by putting a lower bound on the slope of the curve at the inflection points. The bound was specified as a percentage of the slope of the line from the origin to UTS and was initially set to 25%. For each inflection point, the slope was calculated and compared against the calculated bound. If the slope was less than the lower bound the inflection point was rejected. When an inflection point was detected whose slope was greater than the lower bound it was stored away as the possible EDY point. When another inflection point was detected which was greater than the lower its slope was compared to the last point stored. If it was greater, the previous inflection point was replaced by the new inflection point. This process continued until a slope was calculated that was less than the lower bound. The inflection point with the maximum slope was taken as the EDY point and the value for YPE calculated. For most materials the lower bound slope of 25% was sufficient; however, with materials with fairly subtle changes in slope from the region of discontinuous yielding it was necessary to increase this parameter from 25% to up to 100%.

Algorithm Summary

The automatic calculation of YPE requires that the aforementioned algorithm be implemented in software and be performed by a computer. One possible implementation of this algorithm is included in the following in pseudo-code.

ALGORITHM SETUP

- Termination slope = 25% of slope of line from the origin to the UTS point.
- Termination Point = data point number of the yield point.

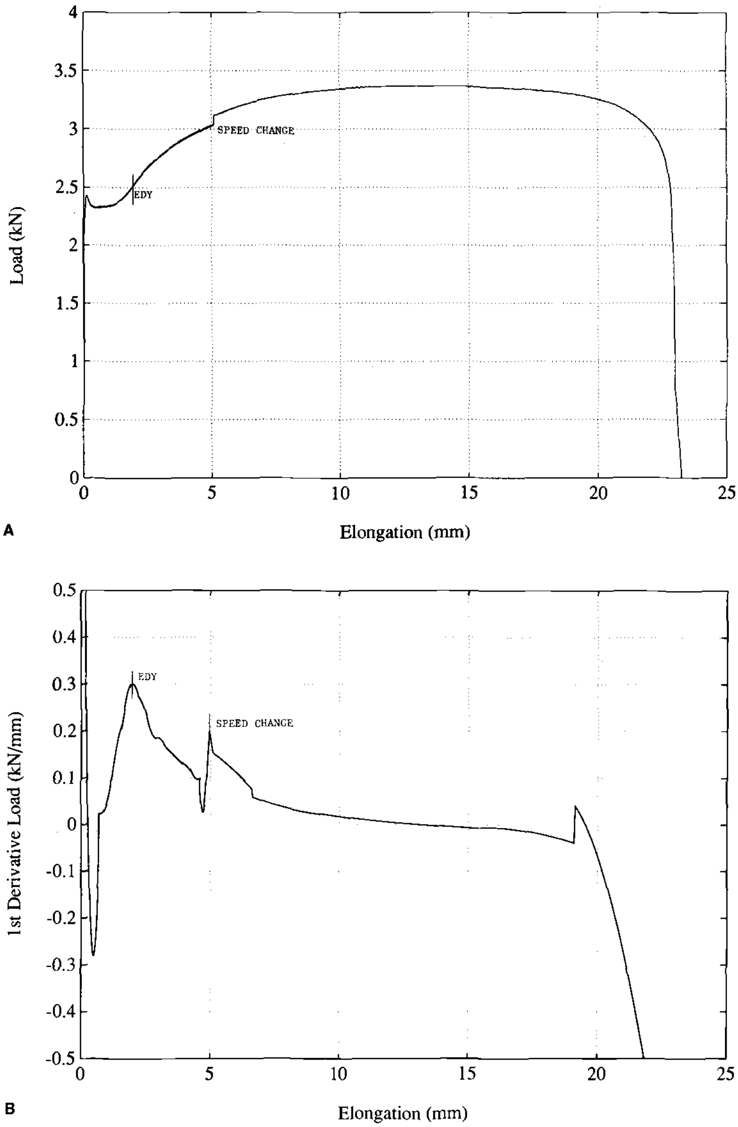
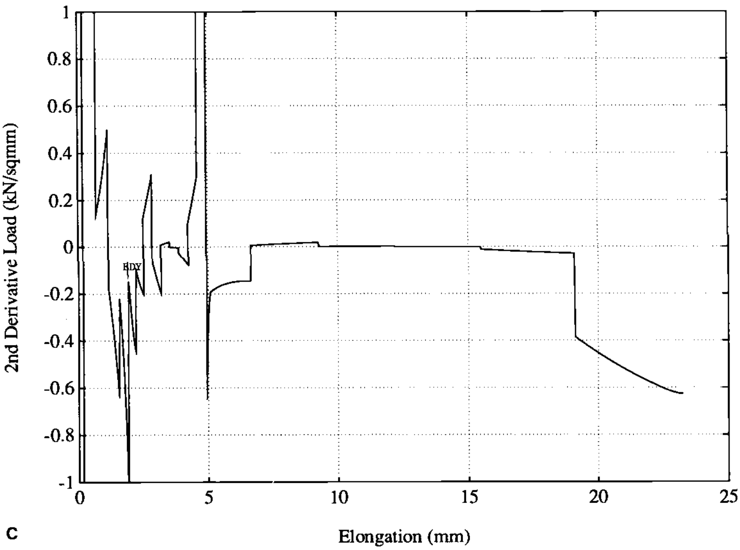


FIG. 7—(a) *Load-elongation diagram for a material exhibiting discontinuous yielding;* (b) *first derivative load-elongation diagram for a material exhibiting discontinuous yielding via piecewise continuous cubic splines;* (c) *second derivative load-elongation diagram for a material exhibiting discontinuous yielding via piecewise continuous cubic splines.*

- N = number of data points acquired/number of regions to be fitted (default to 10 regions).
- Setup array for parametric time: $t[n] = n - N/2$ where $1 <= n <= N$.
- Calculate and invert the sparse array in preparation for solving for the cubic spline.
- Region End = data point number at UTS.



c

FIG. 7—*Continued.*

- IF Speed change occurred AND Speed Change Point Number < Region End THEN Region End = Speed change point number.
- Region Start = Region End − N + 1.
- Initialize the flag for the minimum slope detect: Min Slope Flag = FALSE.
- Initialize EDY Point = 0.

INFLECTION POINT DETECTION LOOP:

- Calculate the coefficients (a_0 − a_3) and (b_0 − b_3) between Region Start and Region End.
- Solve for inflection points t_1 and t_2 using the solution to the quadratic equation.
- Compare the slopes at t_1 and t_2 and choose the point, t_s, with the greater slope.
- IF ($-N/4 <= t_s <= N/4$) AND Min Slope Flat = = TRUE AND slope < Termination slope THEN Exit loop
- IF ($-N/4 <= t_s <= N/4$) AND slope > Termination slope THEN
  IF Min Slope Flag = = FALSE THEN
  Min Slope Flag = TRUE; EDY Slope = Slope; EDY Point = t_s + Region Start + $N/2$
  ELSE IF slope > EDY Slope THEN
  EDY Slope = Slope; EDY Point = t_s + REGION END
- Region End = Region End − $N/2$; Region Start = Region End − N + 1
- IF Region Start < Termination Point THEN Exit Loop

ALGORITHM COMPLETION:

- IF EDY Point > zero, THEN
  YPE = Elongation[EDY Point] − Elongation[Termination Point].

Conclusions

The definitions for YPE and discontinuous yielding as presented in ASTM E 6 were insufficient for the development of an automated algorithm for the calculation of YPE.

Once these definitions were formalized, an algorithm was developed that reduced noise effects on inflection point determination. The algorithm was also designed to adapt to the specimen characteristics by bounding the regions over which the search for inflection points is performed. The result was an automated algorithm for calculation of YPE that is fairly insensitive to material type.

References

[1] Lake, J. S. H. and Flanagan, J. T., "An Automated Tensile Testing Algorithm," *Applied Metalworking*, Vol. 4, No. 2, January 1986, pp. 164–175.

[2] Lancaster, P. and Salkauskas, K. "Curve and Surface Fitting, An Introduction," *Academic Press*, San Diego, 1986.

A. Murray Nicolson[1]

Event Criteria to Determine Bandwidth and Data Rate in Tensile Testing

REFERENCE: Nicolson, A. M., **"Event Criteria to Determine Bandwidth and Data Rate in Tensile Testing,"** *Automation of Mechanical Testing, ASTM STP 1208,* D. T. Heberling, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 91–105.

ABSTRACT: Methods are presented to estimate the errors in estimating peak and slope values in tensile tests when there are limitations due to the electrical bandwidth of the measuring system and the finite data rate of the digital data acquisition system. Various "events" are defined that can occur along the measured stress-strain characteristic. By convolving with the impulse response of a typical low-pass filter, the effects on these waveform shapes is measured, and graphs are shown which relate the error in estimating the peak value or slope as a function of the bandwidth for a known "event" duration. It is shown that for most simple events a bandwidth of 3/(event-duration) is adequate for peak and slope measurements. For data rates it is shown that a rate of about 30 times minimum bandwidth is necessary for errors less than 1% in peak estimates. A simple method of estimating the actual system bandwidth is demonstrated.

KEYWORDS: data rate, bandwidth, impulse response, tensile testing

As the trend towards the accepted form of output from a tensile testing machine shifts from acquiring a trace on a chart recorder to recording a digital data file on a computer, a question frequently asked about the required data rate to meet a given accuracy is: How many samples/second are required to characterize the waveform? It is the purpose of this paper to suggest that, instead, the correct questions should be: (1) What is the bandwidth of the transducer conditioning system required to be in order to give an accurate analog voltage representation of the mechanical system, and (2) What is the required data rate? Without first ensuring that the bandwidth is correct, the user could be collecting large volumes of data at high data rates that are not accurate representations of the measured parameters—the well-known situation summarized as "garbage in—garbage out!"

When pen recorders were in common use as the primary output devices of a tensile machine, the user could usually observe the slew rate of the pen on the chart and become skeptical of the displayed result when the pen moved very rapidly. When the testing machine moved into the digital domain, however, this intuitive feeling was lost, and it has become less easy to judge when errors are occurring. The basic premise of this bandwidth discussion is: As the speed of testing a specimen increases with increasing testing machine crosshead rate, a point is reached where the load or strain signal becomes significantly distorted because of limited electrical bandwidth of the sensor conditioning signal channel.

The intentions of the paper are to come up with simple techniques for the user to quantify required bandwidth, to measure what bandwidth the machine actually has, and (having resolved the bandwidth problem) to identify the required data rate.

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The paper will only deal with the electrical limitations of a testing machine; there are, of course, other limits on accuracy imposed by the mechanical system, such as transducer linearity, alignment, and mechanical stiffness, which are not dealt with here.

Bandwidth

What do we mean by bandwidth? Any sensor conditioning system has a finite bandwidth; the lower limit is always at zero frequency in tensile testing, and it is only the upper limit we need to consider. Apart from filtering after a demodulator, the only reason for having any limit on the bandwidth is **noise,** i.e., random or nonrandom signals not related to the properties of the material being measured; without noise we could make the bandwidth infinite and never be concerned about a frequency limitation. The strain gages used in load cells and extensometers have low voltage outputs, however, so the amplifier gain must be high; hence, these noise levels become significant. The simplest way to reduce noise is to reduce bandwidth, but this will be at the expense of dynamic performance, i.e., the ability of the system to respond to a rapidly changing load or strain signal.

Let's look at an example of this. A common filter used in sensor conditioners has a characteristic called a "2-pole Butterworth." If it has a bandwidth of 1 Hz, its response to increasing frequencies would be as shown in Fig. 1. But this is not very helpful to someone doing a tensile test because we do not know what frequencies to consider. Of greater practical help is the Step Response: How does the system respond to a step change in the input? Figure 2 shows how such a system would respond to a sudden change in input if the bandwidth were 0.3 Hz, 1 Hz, or 3 Hz.

Clearly, the greater the bandwidth, the nearer the output approximates to the input. We have to identify which are the bandwidth-critical measurements that have to be made during a test, and then how to quantify the errors as a function of bandwidth.

Waveform "Events"

We will investigate the effects of bandwidth and sampling rate on seven types of "events" that can occur during a tensile test (Fig. 3).

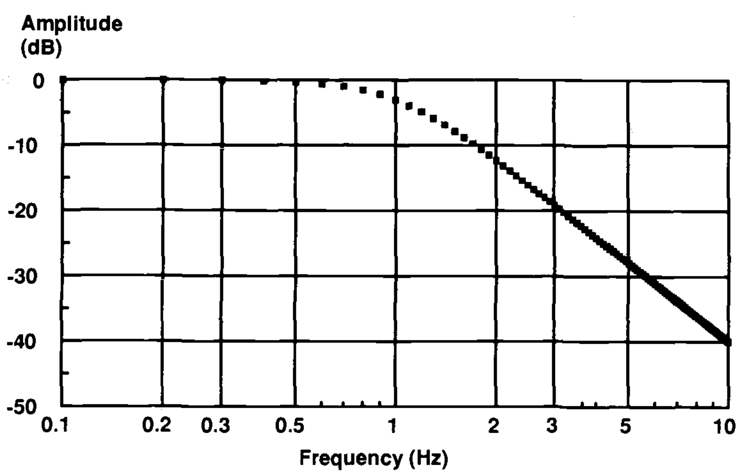


FIG. 1—*Frequency response of a 2-pole, low-pass Butterworth filter with 1 Hz bandwidth.*

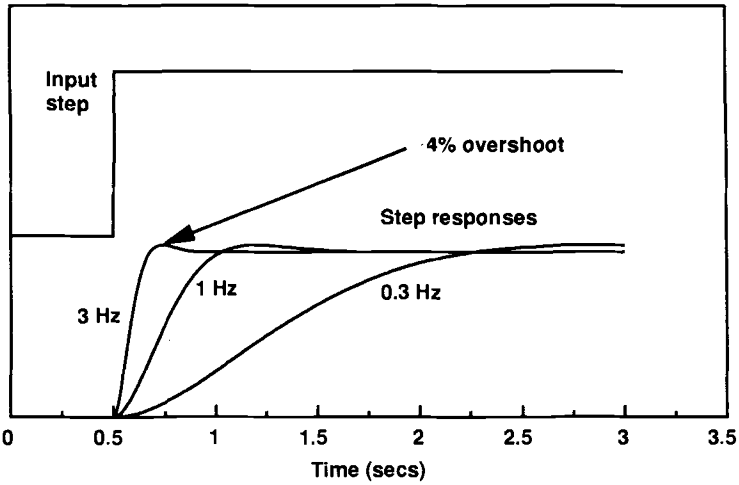


FIG. 2—*Step responses of Butterworth filter with 0.3, 1, and 3 Hz bandwidths.*

The peak measurements in Fig. 3*a* through *f* may be over the whole tensile curve, or they may be only an event occurring within the overall tensile curve (Fig. 4). Here the user wishes to measure accurately the peak values of the intermediate break events, such as fibers failing in a test of a composite material. How do we measure the effect of bandwidth and data rate on such events?

Convolution and the Impulse Response

We have seen we need to find some way to relate the bandwidth characteristics of the measuring transducer channel to the waveform distortion: The solution is to use **convolution in the time domain**. When you know the amplitude **and phase characteristics** of the frequency response of the channel, you can use Fourier transforms to give the corresponding **impulse response** in the time domain: Every filter has its characteristic impulse response. For example, Fig. 5 shows the amplitude and phase characteristics of a simple 2-pole Butterworth filter and the corresponding "impulse response." The impulse response is the output of the system when its input is an infinitely sharp spike at an instant in time.

The effect of a filter with an impulse response $h(t)$ on a waveform which varies with time as $f(t)$ is given by a convolution integral

$$g(t) = \int_{-\infty}^{\infty} f(u) \cdot h(t - u) \cdot du \tag{1}$$

Physically this means that the effect of the filter is obtained by reversing the impulse response waveform, then "dragging" it across the input waveform and cross-multiplying and integrating for each time (t); the output waveform $g(t)$ is "smeared" by the impulse response $h(t)$. As the bandwidth of the filter $H(\omega)$ is increased, the duration of $h(t)$ becomes less and less, and the effect of the convolution becomes less and less, until finally the input waveform is being multiplied by a narrow spike, and the output waveform then looks very similar to the input.

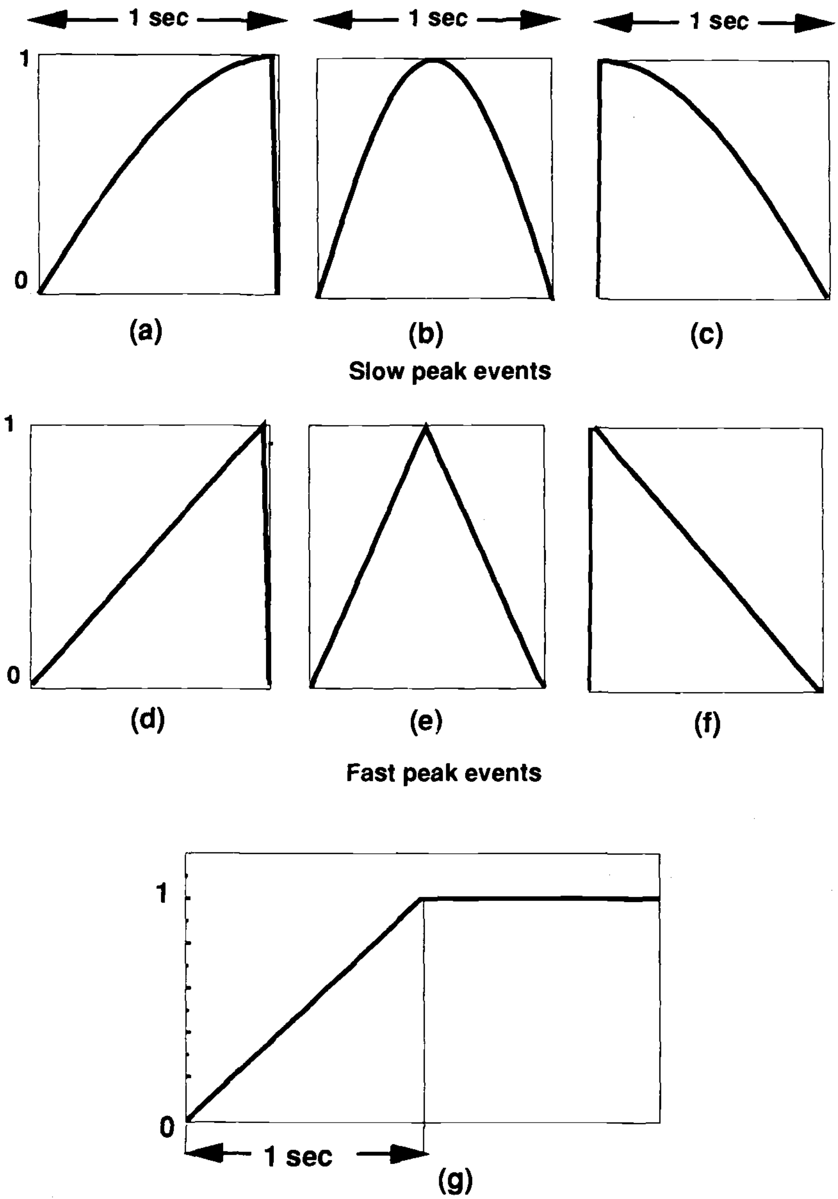


FIG. 3—*Waveform events of 1-s duration to be analyzed for distortion by a filter. Events* (a) *through* (c) *are slowly changing peak events;* (d) *through* (f) *are fast, abrupt peak events; and* (g) *is for slope measurements.*

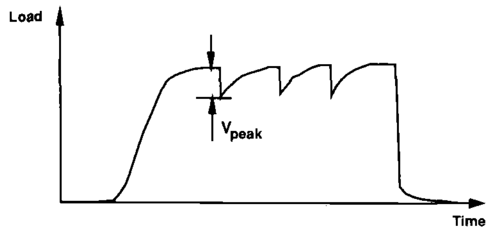


FIG. 4—*How waveform "events" occur in a tensile test.*

The Butterworth Filter Response

To gain an understanding of the effect of bandwidth on waveform events, the 2-pole Butterworth response has been used. This filter is commonly used in signal conditioners, and it has the advantage of a simple analytical form for the impulse response. The frequency response is given by the complex quantity

$$H(f) = \frac{1}{\left[1 - \left(\frac{f}{f_c}\right)^2\right] + j \cdot \sqrt{2}\left(\frac{f}{f_c}\right)} \tag{2}$$

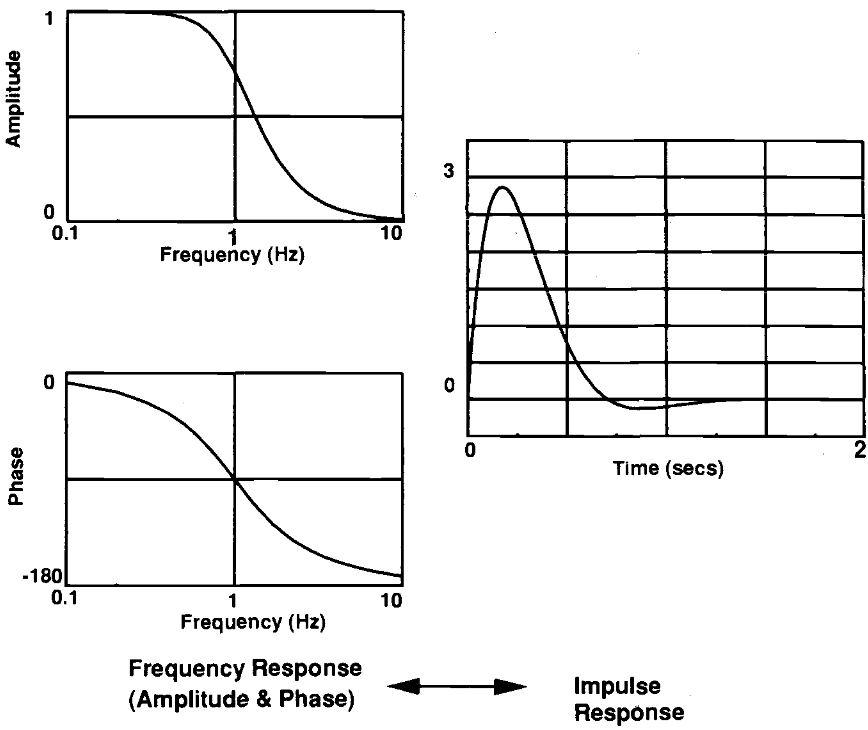


FIG. 5—*Amplitude and phase frequency response corresponding to an impulse response for a 1-Hz filter.*

where f_c is the frequency where the amplitude $|H(f)|$ has fallen to $1/\sqrt{2}$. The corresponding impulse response can be found from Laplace transforms [1] to be

$$h(t) = \sqrt{2}\omega_c \cdot \exp\left(-\frac{\omega_c}{\sqrt{2}} \cdot t\right) \cdot \sin\left(\frac{\omega_c}{\sqrt{2}} \cdot t\right) \tag{3}$$

where $\omega_c = 2\pi f_c$. These characteristics are plotted in Fig. 5 for the case where $f_c = 1$ Hz. Other common filter responses are 4-pole Butterworth and Bessel, but the effects are similar to those given in the following sections.

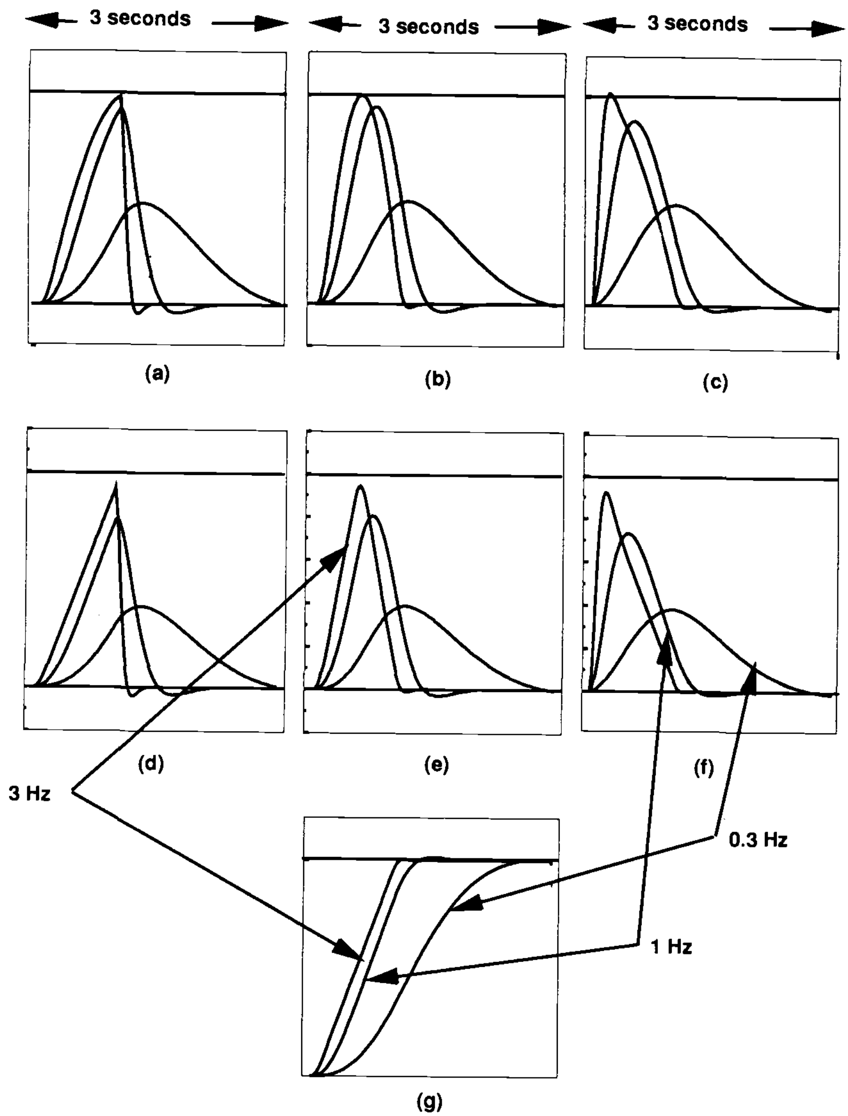
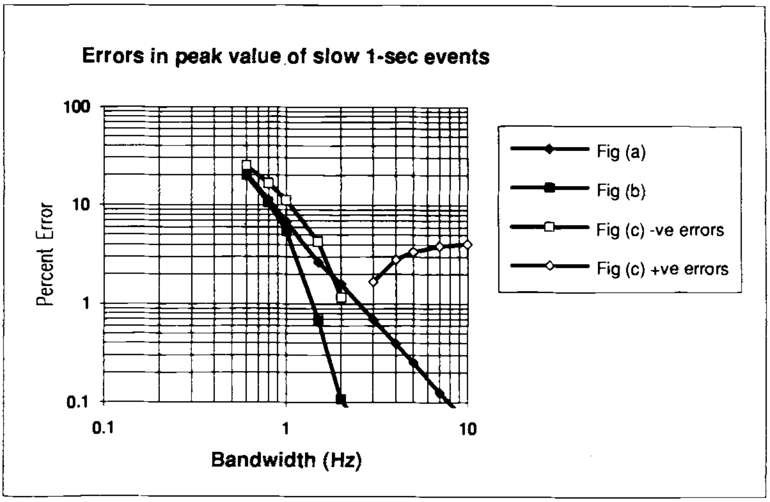


FIG. 6—*Results of passing the waveforms of Fig. 3 through filters of bandwidths 0.3, 1, and 3 Hz.*

Effect on Waveform Events

How the waveform events shown in Fig. 3 are affected by such a 2-pole Butterworth filter can now be illustrated by digital convolution of the impulse response $h(t)$ with the various waveform shapes for an assumed duration of the event τ and an assumed filter cut-off frequency f_c. Examples of these for the waveforms of Fig. 3 are shown in Fig. 6, when the event time τ is fixed as 1 second, for values of f_c of 0.3, 1, and 3 Hz. There are several commercial programs available that can perform digital convolution; results here were computed using Mathcad 3.0 from MathSoft, Inc. We note the point made earlier: as the bandwidth increases, the output waveforms in Fig. 6 more and more closely resemble the corresponding inputs in Fig. 3.



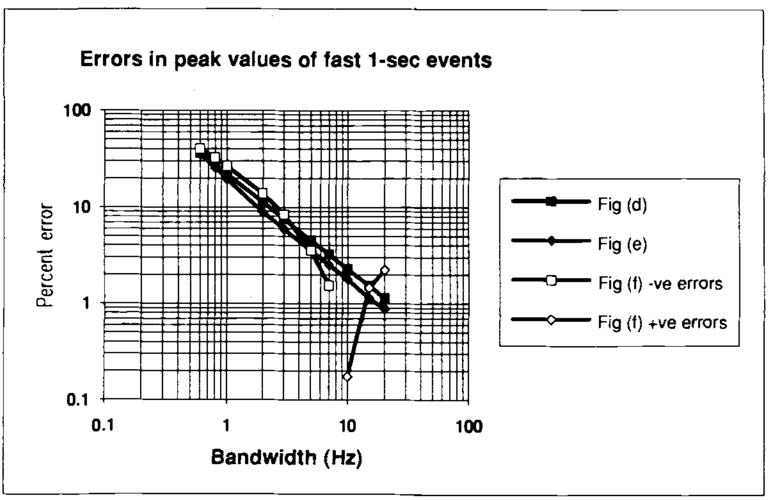


FIG. 7—*How the errors in the peak value of 1-s duration events vary with bandwidth. Note that for events* (c) *and* (f), *the error goes from negative* (*estimate too low*) *to positive* (*estimate too high*).

Effect of Bandwidth on Peak Measurements

We are finally at the position where we can quantify the errors due to bandwidth for these shapes with a 2-pole Butterworth filter response. The duration of each event has been normalized as 1 second, but all the effects will scale. If the event lasts 0.1 second, for example, then the bandwidth effects would be the same at ten times the cut-off frequency, and so on.

If the amplitude of events in Fig. 3*a* through *f* is unity, then the **error** in the peak amplitude as a function of frequency for each was computed and is shown in Fig. 7. Normally the error is found to be negative; the peak value is too low. For events with a fast risetime and slow falltime such as in Fig. 3*c* and *f*, however, the waveform approaches that of the ideal step response of the filter, shown in Fig. 2, which has about a 4% overshoot. Hence in these cases the errors can actually be positive, and therefore the peak value is overestimated.

Conclusion on Bandwidth Versus Peak Measurement

Figure 7 shows that there is a distinct difference between the peak results for (a) through (c) in Fig. 3 versus those for (d) through (f). When the waveform **dwells** at the peak for a short time, then the bandwidth need only be about (3/event-time) in Hertz for an error in the peak below 1%; however, for waveforms more triangular in shape like (d) through (f), the bandwidth must be very much larger for similar levels of error, up to (20/event-time) Hertz. If the "event" amplitude, as in Fig. 4, is only a fraction of the overall signal amplitude, then much larger errors and hence lower bandwidth may be acceptable.

Obtaining the Minimum Data Rate

We have used the 2-pole Butterworth impulse response

$$h(t) = \sqrt{2}\omega_c \cdot \exp\left(-\frac{\omega_c}{\sqrt{2}}t\right) \cdot \sin\left(\frac{\omega_c}{\sqrt{2}}t\right) \tag{4}$$

for our example and now realize that convolving this impulse response with *any* waveform cannot result in a waveform narrower at the peak than the impulse response itself. Even if the input waveform itself were an impulse, the output would be the impulse response itself; and any other shape must have a broader response. So if we can *sample* the impulse response itself adequately to get a small enough error measuring *its* peak, we can be confident that any other peak will be adequately covered. We find where the peak of the impulse response itself occurs, and then the error sampling a distance $t_s/2$ from its peak (Fig. 8).

From differentiation of $H(t)$, we find the peak of the impulse response occurs at $\omega_c/\sqrt{2} \cdot t_{\max} = \pi/4$ and that close to the peak the impulse response can be approximated by

$$h(t)|_{t=t_{\max}} \approx \omega_c \cdot \exp\left(-\frac{\pi}{4}\right)\left(1 - \frac{\omega_c^2 \cdot (\Delta t)^2}{2}\right)$$

$$= \omega_c \cdot \exp\left(-\frac{\pi}{4}\right)\left(1 - \frac{\omega_c^2 t_s^2}{8}\right) \tag{5}$$

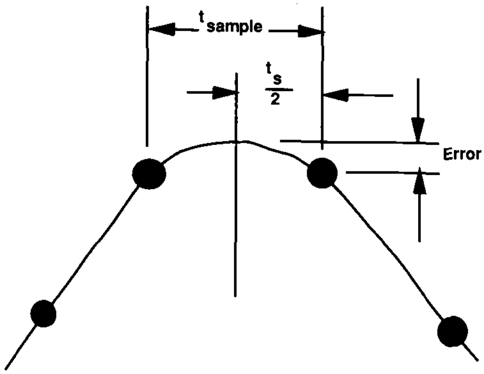


FIG. 8—*Worst case data rate error estimated from the impulse response.*

The fractional error in $h(t)$ at the peak is

$$\text{Error} = \frac{\frac{\omega_c^2 t_s^2}{8}}{1} = \frac{\pi^2 f_c^2 t_s^2}{2} \tag{6}$$

For a 0.5% error at the peak due to sampling

$$\frac{\pi^2 f_c^2 t_s^2}{2} = 0.005 \tag{7}$$

$$\therefore t_s = \frac{\sqrt{0.01}}{\pi f_c} = \frac{0.0318}{f_c} \tag{8}$$

or if the waveform sampling frequency $f_s = 1/t_s$ then

$$f_s = \frac{f_c}{0.0318} = 31.42 f_c \tag{9}$$

Combining Bandwidth and Data Rate Requirements

Now we have a method to combine the necessary bandwidth and data rate. From a knowledge of the time over which the waveform event occurs, we can determine the necessary bandwidth for an acceptable error from one of the curves in Fig. 7, and then we can determine for the additional data rate error the minimum sampling frequency required. For simple waveforms like (a) through (c) in Fig. 3, these data rates can be quite modest: if the test lasts 10 seconds, the bandwidth need not exceed 0.3 Hz for less than 1% error, and hence the data rate need not exceed $0.3 \times 31 = 9.3$ Hz. If the waveform has sharp spikes whose peaks must be determined accurately, however, the bandwidth and data rate requirements can be much higher. In measuring a triangular waveform like (e) in Fig. 3 which lasted 1 second, a bandwidth over 20 Hz would be required and a data rate from the above criteria of $20 \times 31 = 620$ Hz. If such bandwidths and data rates are not available, the test must be run proportionately more slowly.

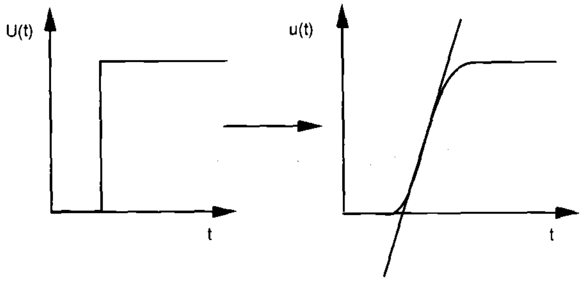


FIG. 9—*Step response gives the worst case slope error.*

Accurate Measurement of Modulus

We can apply similar techniques to determine the bandwidth needed for accurate measurement of slope modulus, as in (g) in Fig. 3 and Fig. 6. The largest slope that can possibly result in when a unit step function $U(t)$ is applied to the filter, resulting in a "step response" $u(t)$ (Fig. 9). The result can be found by convolving the impulse response with $U(t)$ but can more easily be calculated directly using Laplace transforms. The step response of the 2-pole Butterworth filter is readily shown to be

$$u(t) = 1 + \sqrt{2} \cdot \exp\left(-\frac{\omega_c}{\sqrt{2}} \cdot t\right) \cdot \sin\left(\frac{\omega_c t}{\sqrt{2}} - \frac{3\pi}{4}\right) \tag{10}$$

By differentiation we can find the maximum slope of $u(t)$ is

$$\left(\frac{du}{dt}\right)_{\max} = \omega_c \cdot \exp\left(-\frac{\pi}{4}\right) = 2\pi f_c \cdot \exp\left(-\frac{\pi}{4}\right) \qquad S^{-1} \tag{11}$$

We can relate this to the slope of a stress-strain curve as in Fig. 10

$$E = \frac{d\sigma}{d\epsilon} \tag{12}$$

$$\therefore \frac{d\sigma}{dt} = E \cdot \frac{d\epsilon}{dt} \tag{13}$$

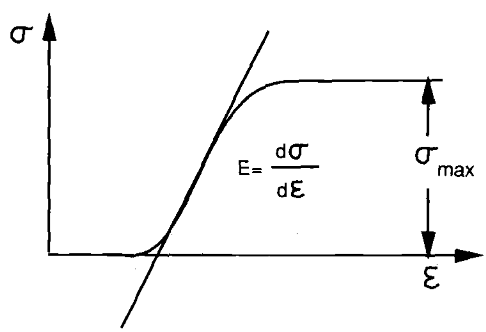


FIG. 10—*Modulus from the slope of the stress-strain curve.*

and normalizing

$$\frac{d\left(\dfrac{\sigma}{\sigma_{\max}}\right)}{dt} = \frac{E}{\sigma_{\max}} \cdot \dot{\epsilon} \tag{14}$$

where $\dot{\epsilon}$ is the strain rate. If we now equate this to the maximum slope that will result from a bandwidth f_c, we have

$$\left(\frac{E_{\max}}{\sigma_{\max}}\right) \cdot \dot{\epsilon} = 2\pi f_c \cdot \exp\left(-\frac{\pi}{4}\right) \tag{15}$$

$$\therefore E_{\max} = \frac{2\pi f_c \cdot \exp\left(-\dfrac{\pi}{4}\right) \cdot \sigma_{\max}}{\dot{\epsilon}} \quad \text{Pa}$$

$$= \frac{2.86 f_c \cdot \sigma_{\max}}{\dot{\epsilon}} \quad \text{Pa} \tag{16}$$

Even if the modulus were actually infinite, we would never measure an apparent modulus greater than $E_{\max}$. This is the limiting case, however; we are more interested in measuring E within, say, 1% accuracy. To compute this, we convolve the impulse response as before with a unit amplitude 1-second ramp as shown in Fig. 6*g* and find how the slope varies from

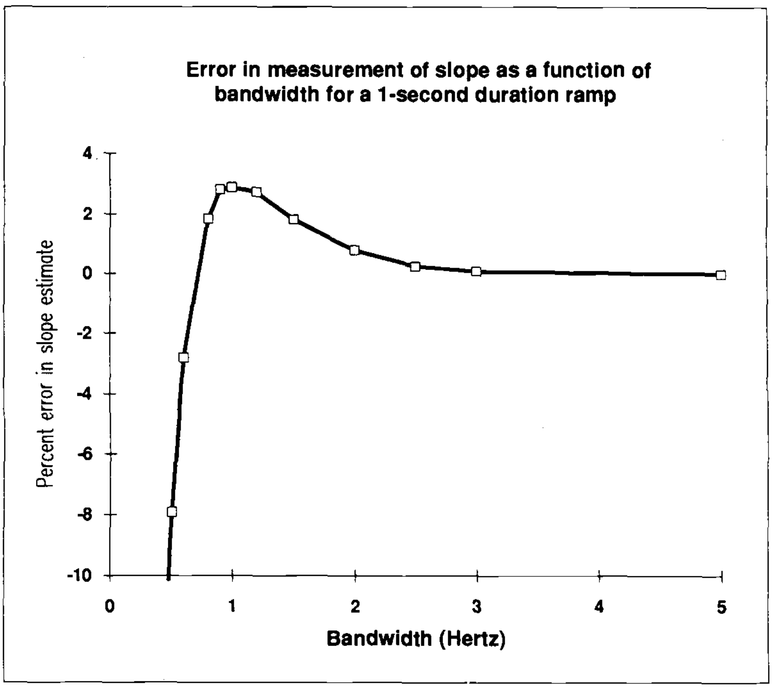


FIG. 11—*How the errors in the slope estimate of a 1-s ramp vary with bandwidth.*

the expected value of unity as bandwidth decreases. Again, the result can be scaled for all other ramps of different nominal ramp rates; i.e., for different strain rates.

The slope was calculated in each case by a method commonly used in algorithms for tensile testing, namely a least-mean-square fit to the data between 20 and 80% of the full amplitude, again using Mathcad. The result of the calculations is shown in Fig. 11. We see that the error rapidly converges to zero when the bandwidth exceeds about 3 Hz.

Note there is a 3% overshoot in the error before it converges to zero at large enough bandwidth; this is again because the step response of the 2-pole Butterworth filter itself has a 4% overshoot, as shown in Fig.2.

The conclusion is that, for errors in slope less than 1% due to bandwidth limitations, the bandwidth should exceed $3/t_r$ where t_r is the projected 0 to 100% risetime at maximum slope.

A Simple Method to Verify Bandwidth

The user needs to measure the bandwidth of the system in use in order to compare it with the bandwidth limits given previously. A simple method to do this that verifies bandwidth of the whole mechanical and electrical load measurement system is to break a high tensile metal wire and record the resulting step response on an analog or digital oscilloscope. For example, Fig. 12 shows the load characteristic on breaking a 0.5-mm metal guitar string on an Instron 4505 machine with the bandwidth selected to be 1 Hz. Also shown are the computed step responses for a 1 Hz 2-pole Butterworth filter, which clearly agree closely.

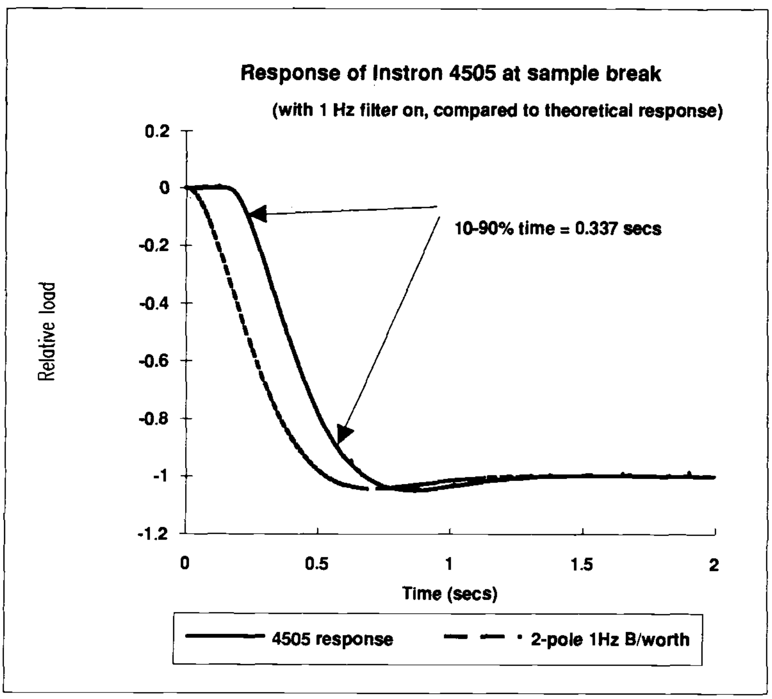


FIG. 12—*Comparison of waveform at break for a high tensile strength wire with the theoretical step response.*

The 10 to 90% risetime of the step measures to be 0.337 s compared to the theoretical values of 0.342 s.

In fact you may measure the 10 to 90% risetime of any system and, assuming it has a similar response, get a good estimate of bandwidth using the graph in Fig. 13, which plots the curve.

$$\text{Bandwidth (Hz)} = \frac{0.342}{t_{10-90}}. \tag{17}$$

Example

An example is shown in Fig. 14 of a tensile test where bandwidth becomes significant. It shows a tensile test on a nonwoven paper at a speed of 10 in./min. At a bandwidth of 500 Hz, mechanical noise in the load channel is seen, which is filtered out when the bandwidth is 100 Hz. Since the curve is similar to Fig. 3*a* and the test duration is about 0.1 s, we would expect from the previous discussion the bandwidth should exceed 0.3/event-time or 30 Hz, and indeed Fig. 14 shows that a bandwidth of 10 Hz there is a significant change in the apparent waveshape.

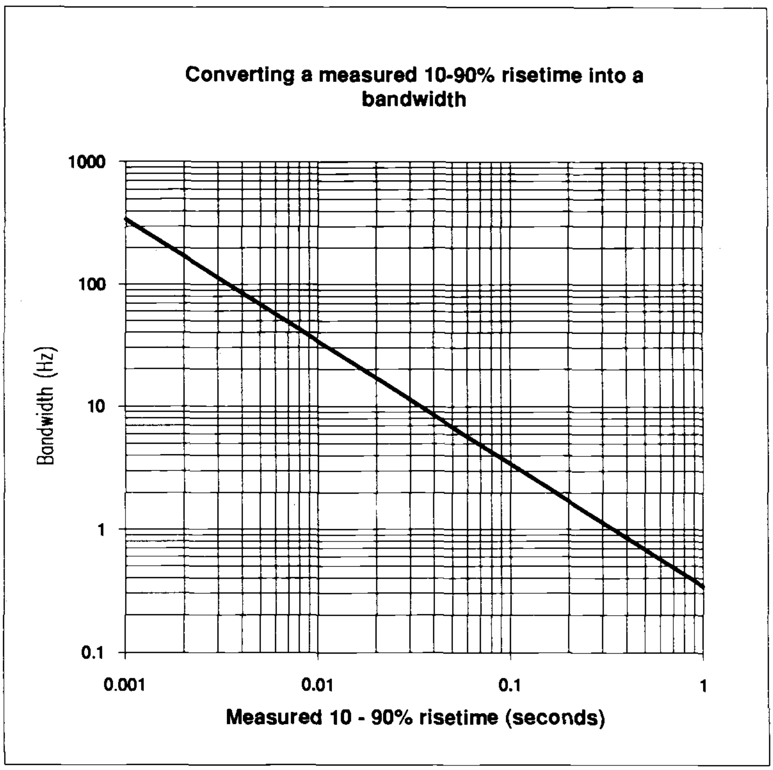


FIG. 13—*The 10 to 90% risetime of the step response gives a quick estimate of bandwidth. The curve plots Bandwidth (Hz) = 0.342/risetime.*

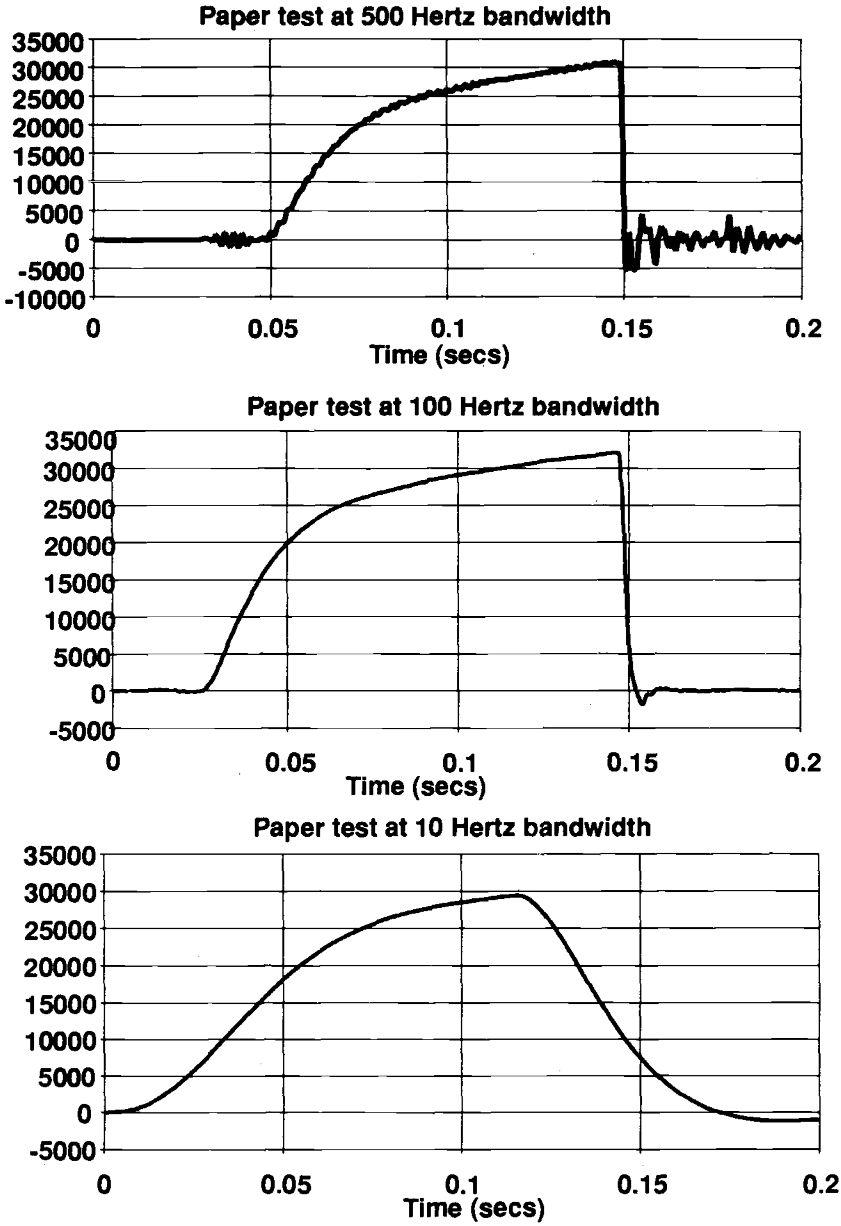


FIG. 14—*Comparison of tests at three different bandwidths, cross-head speed 10 in./min. The test duration is about 0.1 s.*

Conclusion

The main objective of the paper has been to present the argument that the bandwidth of the system *must* be known before specifying the data rate for digital data. To achieve this, it was necessary to find a systematic method to estimate the required bandwidth and data rate for tensile testing. By using convolution of the impulse response with various wave-shapes, we have computed the bandwidths and data rates required to measure the peak values of waveform events to a given accuracy, and the bandwidth necessary to measure the slope to a given accuracy. Further work can be done on the data rate required for slope measurement, which will have more significance to the **scatter** of the slope value than to the absolute error. Work could also be continued on other filter characteristics, although it is not anticipated that the results will differ greatly.

Reference

[*1*] Cannon, R. H., *Dynamics of Physical Systems*, McGraw-Hill, New York, 1967.

ISBN 0-8031-1868-6