Percent Shear Area Determination in Charpy Impact Testing

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Abstract: The Charpy test is used throughout the world in a wide range of industries because of its low cost and the fact that notching and dynamic loading produces a crack tip stress field, which is conservative for many applications. As a result of its widespread use, there is a compelling motivation to extract as much data as possible from the Charpy test. In a Charpy impact test, three key measurements are typically made: total absorbed energy, lateral expansion, and percent shear fracture area. At present, the measurement of absorbed energy and lateral expansion is quantitative and well defined, but the methods used by most laboratories in the measurement of percent shear are qualitative and imprecise. This is ironic for a 100-year-old test because, as discussed in this paper, it can be reasonably argued that percent shear is the most fundamental and physically meaningful of the three Charpy parameters for brittle fracture characterization. Digital image analysis for shear fracture area is shown to be accurate, precise, and easy to use on a routine basis. Recommendations for changes to the ASTM E 23 standard are provided.

Keywords: Percent Shear, Fracture Appearance Transition Temperature (FATT), Charpy Impact Testing, Brittle Fracture, Ductile Fracture, Shear Fracture Area (SFA), Ductile-Brittle Transition Temperature (DBTT), Digital Image Analysis

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Original Charpy Test Development

The first pendulum impact machine was designed by S. B. Russell and coworkers in May, 1896. Actual test results using the pendulum machine were reported in 1897 at an American Society of Civil Engineers (ASCE) conference and were published as an ASCE Transactions in 1898 [1]. Russell tested both smooth and notched specimens and found that notched specimens were preferred for testing ductile materials because the specimen could be completely fractured when notched. The pendulum impact machine had been conceived by Russell to enable the measurement of the energy absorbed by the specimen during fracture, and this machine was a prototype of the pendulum machine used throughout the world today as specified in ASTM Standard E 23, "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials".

In 1901, a French researcher named Charpy published his work—the second publication in the world on pendulum machine testing—on notched bar pendulum impact tests [2]. Charpy's tests used a pendulum impact machine based on the design developed by Russell. Because of Charpy's early involvement with the notched bar pendulum impact test and his work toward standardization, this test is referred to throughout the world today as the "Charpy" test. The original focus of the pendulum machine was on the measurement of absorbed energy [3, 4]. Other parameters from the Charpy test, in particular lateral expansion and percent shear, were investigated much later.

Historical Perspective on the Use of Percent Shear

No seminal paper identifying shear area as a key Charpy parameter was found in the literature search for this paper. This is due, in part, to the fact that titles and abstracts of early papers in the field were apparently not focused specifically on percent shear fracture area alone. Nevertheless, papers dating back to the late 1800s have mentioned the importance of fracture surface examination in dynamic testing. For example, in Reference [5], photographs of fracture surfaces were reported for various grades of wrought iron and used as part of the analysis to determine the adequacy of the castings for gun barrel applications. The Reference [5] paper was mentioned in the 1902 review report [6] on the state of knowledge concerning impact tests in the time period up to 1902. We did not find any papers or reports in the Reference [6] bibliography to shear area measurement or fracture appearance transition temperature (FATT). Similarly, Reference [7] was published in 1925, and presented a history of important developments in impact testing up to that time. Again, since no references to shear area measurement or FATT were reported, we have concluded that these parameters were not in use up to at least 1925.

Considering the historical progression of the ASTM E 23 standard from 1947 to 1981, a total of six revisions (E23-47T, E23-56T, E23-64, E23-66, E23-72, and E23-81) to the standard were issued. There is no mention of shear area measurement in the 1947 standard. However, there was one mention of fracture surface examination in the 1947 version which stated, "So pronounced is the effect of temperature on the ability of steel to stand up in service when notched, that comparisons are frequently made by examining fractures and by plotting energy value versus temperature from tests of notched bars at a series of low temperatures". The Report section of the standard only mentions energy as the key Charpy parameter.

The 1956 standard contains a similar statement to that of the 1947 standard, but adds that fracture appearance versus temperature is a useful plot. The quote from the standard follows: "So pronounced is the effect of temperature on the behavior of steel when notched that comparisons are frequently made by examining specimen fractures and by plotting energy value and fracture appearance versus temperature from tests of notch bars at a series of temperatures". The 1956 standard also includes a note on some of the definitions of transition temperature which may be found using shear area: "Note 2 – Some of the many definitions of transition temperature currently being used are: (a) the lowest temperature that exhibits a fibrous fracture, (b) the temperature where the fracture shows a 50 per cent fibrous appearance, (c) the temperature corresponding to the energy value 50 per cent of the difference between values obtained at 100 per cent fibrous and 0 per cent fibrous, and (d) the temperature corresponding to a specific energy value". The 1956 standard also required, under Report requirements, "(8) Appearance of fractured surface". Since there was no guidance on how to make this measurement in the 1956 standard, it must be assumed that the user of the standard could apply any method desired, the simplest being a statement that there was, or was not, a brittle region on the fracture surface.

Finally, the 1981 standard provided four methods for determining percentage shear fracture area which are similar to today's standard, and stated that fracture appearance should be reported when required. There was also a note in the 1981 standard which said, "Note 9 – Because of the subjective nature of the evaluation of fracture appearance, it is not recommended that it be used in specifications".

Several industries today require that shear fracture area (SFA) be measured, but as a Charpy parameter, it is not widely used. This is probably due to the difficulty in measuring percent shear to any reasonable degree of accuracy and to the historical perspective as delineated in Note 9 of the 1981 standard.

Current ASTM E 23 Methods

In the present E 23 standard [8], there are five methods for determining the percent shear fracture area. The five methods, presented in ASTM E 23 in increasing order of precision, are listed below:
1. Measure the length and width of the flat fracture region of the fracture surface and determine the percent shear using tables in the standard.
2. Compare the appearance of the fracture of the specimen with the fracture appearance chart in the standard.
3. Magnify the facture surface and compare it to a precalibrated overlay chart, or measure the percent shear fracture by means of a planimeter.
4. Photograph the fracture surface at a suitable magnification and measure the percent shear fracture by means of a planimeter.
5. Capture a digital image of the fracture surface and measure the percent shear fracture using image analysis software.

The method most used in industrial applications is the photograph comparison method (method 2) because of its simplicity and low cost. However, this method's inherent error is at least ±5 %, provided the correct photograph can be identified. That is, given a classical fracture surface of a full-sized Charpy specimen, the shear fracture area can only be stated to a degree of certainty of ±5%. If the operator's judgment is incorrect by one photograph, the error becomes 15%. As discussed later in this paper, measurements on "textbook" fracture surfaces have resulted in average errors on the order of 20 % shear area, with the largest deviation being on the order of 55 % shear area. With these large margins of error, a better method should be used to provide reliable, quantitative data, and we have recommended that users of the standard be appropriately warned concerning the poor precision and accuracy of the photograph comparison method.

The area measurement methods such as the digital imaging method (method 5) and the planimeter method (method 4) have higher precision than the photograph comparison method (method 2). Although method 4 and method 5 have similar precision, digital imaging is expected to be favored by industry in the coming years, especially for applications in which accurate measurement of percent shear is needed.

Validity of Shear Fracture Area as a Charpy Parameter

Before discussing the analysis for SFA measurement methods, it seems appropriate to present the argument for SFA as an important and fundamental Charpy parameter. In order to set the proper context for this discussion, we must first define the need for the Charpy test. In particular, what is needed is a simple and cost-effective test that can provide useful data for protection against brittle fracture in components and structures. Of course, the Charpy test can also be used for protection against ductile fracture, which is important in applications such as upper shelf energy drop in nuclear pressure vessels due to neutron irradiation. It is also beneficial as a comparison test for ductile fracture evaluation in general. However, we will limit our current discussion to brittle fracture applications for consideration of SFA measurement technology.

All body-centered-cubic materials undergo transitional fracture behavior over some temperature range. This means that the material will be 100% brittle below a certain temperature and 100% ductile above a higher temperature. The intermediate temperature range is referred to as the transition region where the fracture is mixed mode. The traditional definition of mixed mode is a fracture surface where there is one separate region of brittle fracture surrounded by a second region of ductile (fibrous) fracture. An example of mixed mode fracture is shown in Figure 1, and Figure 2 shows the load-deflection behavior observed when a specimen fractures in the transition region. Referring to Figure 2, the crack forms in the specimen at the notch root as the loading increases to the peak load level. Stable crack growth initiates at the notch in the center region where the stress intensity factor is highest and spreads along the root of the notch toward the free surfaces. Just prior to peak load, the stable crack is formed and begins to propagate into the uncracked ligament. The load decreases as a result of the load-carrying area reduction, and the stable crack propagates until the brittle crack initiates. Brittle fracture is signaled by the rapid load drop which indicates the microsecond time scale brittle crack advance.

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The remaining energy after brittle fracture is expended in tearing the shear lips and in bending/fracturing the plastic hinge at the rear of the ligament. For tests near the lower shelf, brittle fracture occurs during initial load rise, well before reaching peak load. For tests on the upper shelf, the load-deflection curve is similar to that of Figure 2, but there is no vertical unloading due to brittle fracture. Since the SFA is proportional to the height of the brittle fracture unloading, physically based correlations have been developed to calculate the SFA based on the brittle fracture initiation and arrest loads.

Percent shear is arguably a physically more meaningful Charpy parameter than absorbed energy for protection against brittle fracture. There are at least four arguments in favor of using SFA in conjunction with absorbed energy to define a ductile-brittle transition temperature (DBTT) for ferritic materials:

- There is no physical reason why the SFA transition curve should coincide with the absorbed energy transition curve. Therefore, the Charpy parameter that is used to define DBTT should be selected based on the applicability of the parameter to the in-service component.
- DBTT is usually defined as a temperature below which fracture occurs nearly entirely by cleavage. Safe temperature limits for structures should be based primarily on FATT since this index is a fracture-based index.
- Absorbed energy is not a fundamental material property (as opposed to, for example, fracture toughness) and should only be used when it is supported by other meaningful parameters such as SFA, or is backed by in-service structural failure data.
- SFA can be used directly to relate fracture appearance data from miniaturized and subsized specimens to full size specimens, provided the miniature specimen stress fields reasonably simulate the full size Charpy fields.

One illustration of the drawback associated with the use of the energy parameter is in the nuclear industry where neutron damage causes a shift in the absorbed energy as neutron damage increases. The nuclear industry tracks pressure vessel embrittlement using the 30 ft-lb Charpy index. In general, as a result of neutron damage, the Charpy energy-temperature plot exhibits three changes: the energy-temperature curve is shifted to higher temperatures; the slope in the transition region decreases; and the upper shelf energy drops. As a result of these neutron damage effects, the SFA level corresponding to the 30 ft-lb index, changes continuously throughout the irradiation. This phenomenon is illustrated graphically in Figures 3 through 5. As shown in Figure 3, the change in SFA does not increase proportionally to the Charpy shift measured at 30 ft-lbs (ΔT_{30}). Case 1 shows a material with a low upper shelf energy (USE) and a significant decrease in slope in the transition region. This results in an irradiation induced change in SFA at the 30 ft-lb index of about 45% (see Figure 4). For this particular case, since the shelf drop and slope decrease are large, the 30 ft-lb index crosses the transition curve at a point on the post-irradiation curve that corresponds to a very large SFA level. Case 2 shows a change in SFA at the 30 ft-lb index of about 18% for another weld irradiated to a higher fluence but with a comparable ΔT_{30}. In this case, the shelf drop and transition slope change are not large, and the 30 ft-lb index crosses the transition curve at a point on the post-irradiation curve that

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corresponds to an SFA level which is close to the unirradiated value. Therefore, there are clearly cases where neutron damage monitoring using an energy index will result in significantly different SFA values in the irradiated materials. This means that the use of a fixed energy parameter can yield neutron embrittlement data that are based on a continuously changing SFA level.

An illustration of the second bullet above is given in Reference [9] which highlights the inconsistencies that can occur between Charpy energy and fracture appearance. Results from a Charpy test for a weld metal are reported, showing high energy and other evidences of good ductility, but the SFA is only 20 %. This particular specimen was not completely fractured into two separate halves since it passed through the anvils as one piece, the lateral expansion was about 11%, there were large indentations in the specimen from the anvils, but the fracture surface showed 80% cleavage across the center of the surface. Reference [9] also reported instrumented striker data and concluded that some materials have high resistance to crack formation at the notch but exhibit very low resistance to brittle crack propagation. In such cases, the absorbed energy can be high but the fracture surface exhibits predominantly brittle fracture. Further evidence was reported in Reference [9] for as-welded and stress relieved material which exhibited ~40 C differences in temperature at the middle of the transition region between the energy-temperature plots and the SFA-temperature plots.

It can be reasonably deduced from the examples above that SFA is not only a useful Charpy parameter, but also an informative, necessary parameter that should be considered when results are applied to an in-service component.

Percent Shear Measurement using Digital Imaging

Since the focus of the rest of this paper is on digital imaging, it is seems fitting that we should define exactly what is meant by digital imaging technology. Digital imaging systems can use image analysis technologies for easy, accurate, and precise measurement of percent shear fracture area. These systems generally consist of a camera, lens, lighting, data acquisition software, and image analysis software. Percent shear measurement via this method involves capturing the image of the fracture surface, outlining the brittle area, and outlining the outside region of the fracture surface. The software automatically integrates the areas to determine SFA. There have been a number of recent advances, such as the use of a telecentric lens (Figure 6) that make these systems more accurate and precise. Even still, the accurate measurement of percent shear is not a changeling application for most modern systems. While the telecentric lens greatly reduces parallax distortion and other optics problems such as lens axis perpendicularity, a recently developed two-dimensional calibration technology eliminates residual errors in the optics. With this technology, it is possible to re-map the pixel grid to yield a nearly undistorted image. In the results reported here, state-of-the-art imaging technology was used that incorporates these features.

Digital Imaging System Precision and Accuracy

A multi-phase study was conducted to validate the digital imaging system precision and

accuracy. The first phase of this work consisted of a calibration study, in which one technical staff member, as well as a non-technical staff member, used a digital imaging system to determine the accuracy and precision of the method. To determine the accuracy of the digital imaging system, a precision reticle with length accuracy of $\pm78.7\mu$in ($\pm2\mu$m) and 196.7μin (5 μm) line width, was used. A 0.2- by 0.2-inch (0.51- by 0.51-cm) square area was outlined using the software, and the resulting areas are summarized in Table 1. A mean value of exactly 0.04 in^2 (0.26 cm^2) would result in perfect accuracy. As shown, the measured values are accurate to within ± 0.06 % on area, which indicates that the digital imaging system is very accurate, and good results can be obtained by staff with no formal training in engineering or other technical fields.

To demonstrate the precision of the digital imaging system in a typical shear area application (without using precision-made tooling such as the reticle), the digital imaging system was used to measure the percent shear of a LaserJet printout of a 1:1-scale CAD drawing of a Charpy bar with areas drawn which give 20%, 40%, 60%, and 80% shear (Figure 7). Technical staff members knowledgeable of Charpy impact testing, as well as a non-technical assistant, used digital imaging systems to determine the simulated percent shear areas. The brittle areas were denoted by the inner square or circle center, while the ductile areas were defined by the remaining outer area. Both square and circles were used to simulate the various contours outlined on a typical Charpy bar.

The data shown in Table 2 summarize the averages and standard deviations after three separate percent shear measurements by each participant. The accuracy of the digital imaging system could not be verified with this method due to CAD drawing uncertainty and printer distortion. As shown in Table 2, the digital imaging system proved itself to be precise, with a maximum standard deviation of 0.3 % shear area. These results also show that lab-to-lab, the digital imaging system precision is consistent.

These two simple experiments display three important features of the digital imaging software. First, the digital imaging software is easy to use. Both technical and non-technical personnel were able to use the software and obtain comparable results. Secondly, the digital imaging system provides accurate results for cases where the simulated fracture surface can be clearly identified. Lastly, the system provides precise results.

Image Analysis of Textbook Fracture Surfaces

An inherent downside to the measurement of percent shear is the bias of the operator. Here, we define bias in terms of the operator's ability to clearly identify the brittle region of fracture. In some instances, the fracture surface may not exhibit classical faceted and shiny regions. In other cases, the inexperience of the operator may play a role. Therefore, the second phase of this study was conducted to examine these types of bias. Thirteen specimens of various ductility levels ranging over the transition region were studied. The analyses were conducted without any collaboration between the organizations. The specimens chosen were "textbook" specimens, having clearly defined areas of brittle fracture. The set of specimens was studied using the photograph comparison method as well as the digital imaging technology.

The results are shown in Figure 8 and in Tables 3 and 4. These results show that, when trained personnel in the Charpy impact testing field use digital imaging to analyze specimens containing definitive brittle areas, the percent shear values are precise. The average percent difference between laboratories was only 1.5 % shear, and the maximum difference for any single measurement was only 4 % shear. Since three engineers were able to obtain very similar results, and since the previous section of the paper has established that any region that can be seen can be accurately integrated to obtain the correct area, we have concluded that the image analysis results are also accurate.

A comparison of the digital imaging data and the photograph comparison method is shown in Table 4. The average difference between the digital imaging result and the photograph comparison method is 19.6 % shear, with the largest deviation being 55 % shear. Figure 8 also shows that photograph comparison results, at percent shear levels over about 90 %, are accurate for all participants. In the lower data range, the Engineer 3 seems to display a bias using the photograph comparison method toward low values. On the other hand, Engineers 2 and 3 tend to be biased high for percent shear measurements in the 50 to 90 % shear range.

Based on experience and these results, it is recommended that the E 23 standard should only allow the photograph comparison method as a qualitative approximation of SFA. Furthermore, techniques such as digital imaging and the use of a planimeter should be recommended as the primary SFA measurement methods.

Analysis of Subsize Round Robin Specimens

In many industrial applications, the conditions for measurement of SFA are far from ideal. Therefore, in the third phase of this study, we measured a set of specimens used in a round robin organized by Lake Erie Steel (LES). In the round robin, five companies analyzed the percent shear of 87 specimens of various sizes (mostly subsized Charpy specimens). These participants used either the photograph comparison method or the planimeter method.

MPM Technologies, Inc. (MPM) and the National Institute for Standards and Technology (NIST) used digital imaging to evaluate the 87 round robin specimens. Unlike the actual participants in the round robin, however, we established several criteria for analyzing the specimens. This allowed us to better classify the various abnormalities as either ductile or brittle. Further details concerning the fracture surface interpretation guidelines are discussed later. Therefore, comparisons between MPM/NIST data and the data of the five participants should be made with these in mind.

Digital Analysis Procedures for the LES Round Robin

As previously discussed, percent shear measurement via digital image analysis involves capturing the image of the fracture surface, outlining the brittle area and outside region of the fracture surface, and automatic software integration of the areas to determine SFA. Typically, specimens exhibit clear indications of brittle and ductile fracture areas. However, the LES round

robin specimens were mostly subsize specimens with extensive plastic deformation. In addition, the materials tested showed mixed ductile/brittle fracture (localized mixed mode fracture), and, in several specimens, cracks normal to the main crack plane were observed (Figure 9). These characteristics on the fracture surface necessitate special analysis procedures. To ensure consistent data measurement, the following procedure was used for determining percent shear:

1. Calibration with a precision target was done before each day of measurements.
2. Each specimen was examined under a stereoscope and notes were taken on its fracture appearance.
3. As shown in the examples in Figures 9 and 10, a digital photograph of each specimen was taken at approximately 11X magnification, and the brittle area and outer area were outlined in the software.
4. The percent shear and areas were calculated and recorded in a spreadsheet and plotted (Figure 11).
5. A screen shot of the photographed specimen and outline was printed on a color printer for reference.

Several assumptions were made pertaining to the calculation of the brittle area. These assumptions are important since the atypical fracture surfaces of these specimens are not anticipated in the ASTM E 23 standard. The irregularities include, but are not limited to: large amounts of plastic deformation; localized mixed mode fracture (that is, an area with evidence of ductile fracture with "pockets" of brittle fracture); fracture surface oxidation; and cracks perpendicular to the main fracture plane. These characteristics make the fracture surface analysis difficult as they extend beyond the scope of the E 23 standard. With these factors involved, we developed a set of criteria to make our analysis more consistent between operators:

- First, the analysis was performed in accordance with the guidance of E 23 whenever possible.
- Second, the total area was measured based on the post-fracture total area. That is, plastic deformation is included in the total outer area calculation (not the uncracked ligament area).
- Third, all flat regions characteristic of fast fracture (especially on oxidized specimens where there were no decisive faceted, bright, shiny regions) were considered to be brittle areas.
- Fourth, crack openings perpendicular to the fracture surface, even if shiny on the inner crack enclave region, were not included in the brittle area calculation. This is because the opening of the crack is due to plasticity and its area should not be in the brittle are calculation.
- Finally, any area with localized mixed mode fracture ("pockets" of brittle fracture in the ductile region) was said to be 100 % brittle. This criterion was adopted in order to provide conservative results for end users in terms of safety of structures.

Each of these assumptions is consistent with the spirit of the E 23 standard and provides a conservative measurement of the undesirable brittle fracture percentage. With these factors in mind, each specimen required careful examination.

Round Robin Digital Analysis Results

The digital analysis results are plotted in Figure 11. The data for the two independent imaging systems shows an average difference of 4.3 % SFA over the 87 specimens measured, and a maximum difference of 15.1 % SFA. It is interesting to note that the agreement is very close for SFA measurement up to about 50%, and it is again close at levels in excess of about 80 %. The transition region SFA data in the 55 % to 80 % range are more scattered due to mixed mode fracture regions and other effects such as cracking normal to the main crack front. In this region of SFA, differences between results were as large as 15 % SFA. These differences are due to the bias of the operator since the brittle area for some specimens was very difficult to see. Reference [9] reported results for a round robin using conventional Charpy specimens. In that study it was concluded that the level of agreement among participants was greatest when they were experienced, the results were close to the FATT, and simple, two-dimensional photographs were used for comparison. The Reference [9] work, as well as the current study, point to the importance of having well established rules for interpretation of the fracture surface features to minimize bias of the analyst.

Round Robin Results for the Five Participants

As shown in Figure 12, data obtained via a combination of the photograph comparison method and the planimeter method resulted in a great deal of scatter. Differences as large as 70 % shear were reported, and the average maximum to minimum difference of the 5 participants for the 87 specimens was 41.9 % SFA. The subsized specimens are even more difficult to accurately analyze using photograph comparison, since only full-sized specimens are pictured in the current ASTM E23 standard. In addition, the specimens were hard to analyze due to the presence of oxidation, splits, and high levels of plastic deformation. Further discussion of the round robin results follows.

Figure 12 shows a much larger amount of scatter from lab-to-lab in the determination of percent shear by the five LES round robin participants. At this poor level of accuracy and low precision, further analysis of the round robin data is not meaningful other than to note that the scatter for the five labs is somewhat lower at the low and high SFA levels.

As discussed earlier, two sources for the scatter have been identified: operator bias and method error. The error caused by an operator's bias is simply an operator's inability to see and/or to physically interpret what is seen as either brittle area or ductile area. Method error, on the other hand, varies significantly according to the method used. To date, the two methods that are most commonly used are the photograph comparison method (method 2 listed in the ASTM E 23 standard) and the digital imaging method (method 5 listed in the E 23 standard). Between these, the photograph comparison method is the most widely used in the steel industry. However, this method, according to the E 23 standard, is the second least accurate method in measuring percent shear. Therefore, given the difficulty in comparing subsize photographs to full size, and the highly deformed fracture surfaces, it would be relatively easy to be three or four photographs away from the correct photograph, resulting in error bands on the order of 40 to 70% shear, which is observed in Figure 12. The digital imaging method, as shown in the earlier

portions of the paper, however, nearly eliminates the method error. The much closer agreement of the MPM and NIST digital imaging results demonstrates this point.

Percent Shear Area from Instrumented Data

Most industries that use Charpy parameters for regulation or as a material acceptance criterion use the absorbed energy parameter. It is likely that absorbed energy was selected over percent shear because, in the past, accurate measurement of percent shear was tedious since it required area integration using a planimeter. Additionally, some materials do not exhibit clear evidence of brittle fracture on the fracture plane. For these materials analysis using optical imaging is not possible. However, there are available today, optical imaging systems which are easy to use and which give very accurate results. Modern instrumented striker test systems can provide very accurate Charpy load-deflection data that can be used to determine the brittle crack initiation load and crack arrest loads. These critical loads can be put into physically based models for calculation of the percent shear fracture area. This solves the problem of not being able to see brittle areas on the fracture surface, especially known to occur for some weld metals. The use of critical loads to determine SFA can also be used in conjunction with optical methods to check results of the direct measurements. Although the use of instrumented data in conjunction with digital imaging to determine SFA has not been used much in the past, we recognize this as a powerful tool for the future determination of accurate SFA data.

Recommendations for ASTM E 23 Standard

It is recommended that the E 23 standard be amended to include important changes related to SFA measurement and reporting. A summary of the proposed changes to the standard follows:

- The standard should clearly define the total area for percent shear calculation as the total post-fracture area measured on the sample. The standard does not currently state that the plastically deformed area is included in the total outer area calculation. Some users may incorrectly assume that the outer area is calculated based on the uncracked ligament area.
- All flat regions (where there is no decisive faceted, bright, shiny regions) should be considered to be brittle (fast fracture) area.
- Any crack perpendicular to the main fracture surface, even if shiny on the inner crack enclave region, must not be included in the brittle area calculation. This is because the opening of the crack is due to plasticity, and its area should not be in the brittle area calculation.
- Any area with localized mixed mode fracture (that is, an area with evidence of ductile fracture with "pockets" of brittle fracture) should be defined to be a 100% brittle region on the fracture surface. This criterion is recommended in order to provide conservative results for end users in terms of safety of structures.
- The ranking of methods should be carefully quantified to indicate the expected accuracy and precision that can be obtained. Based on experience and the results

from the textbook specimen analysis of this study, it is recommended that the E 23 standard should only allow the photograph comparison method as a qualitative approximation of SFA.

- Direct area measurement techniques such as digital imaging and the use of a planimeter should be recommended as the primary, recommended methods. Other methods, such as photograph comparison, should be moved to an Annex and defined as alternative methods of low accuracy for use only in cases where area measurement techniques are not available.

- Additional recommendations to reduce operator bias should be added to the standard. For example, these recommendations can include analyst training, establishing rules to define the brittle fracture region, the use of optical stereoscopes, and the use of instrumented striker data.

- Percent shear should only be measured on samples tested in the transition region where mixed mode fracture occurs. For example, a material showing a fully ductile instrumented curve (no sudden drop due to fast fracture) is by definition 100 % ductile. Users should not be confused by the fact that upper and lower shelf SFA can be determined without the need for image analysis, and instrumented striker data can be used exclusively to define this behavior.

- The use of supplementary techniques should be recommended to check the digital imaging whenever possible. Examples include load-deflection data from instrumented strikers and examination under the stereoscope. In cases where instrumented striker data are available, the 100 % shear and 100 % brittle specimens can be identified based solely on the instrumented striker signal. The instrumented striker is extremely accurate for determination of whether there are brittle fracture events during a test. Further, equations have been developed that use the instrumented striker brittle fracture initiation and arrest loads to calculate SFA, and these can be used to check the digital image measurements.

Summary and Conclusions

In summary, the accuracy and precision of digital analysis methods are found to be more than adequate, as expected, with results similar to the planimetric methods previously used. Our overall conclusion is that if the brittle fracture area can be seen optically, percent shear fracture area can be measured precisely with high accuracy. As the complexity of the fracture surface features increase, however, error due to operator bias is expected to increase. Digital analysis results from the "textbook" series, compared with the subsized round robin samples, quantify this observation well: an average difference of 1.5 % SFA and a maximum difference of 4 % SFA for "textbook" fracture surfaces defines the low bias case; an average difference of 4.3 % SFA, and a maximum difference of 15.1 % SFA for the round robin specimens defines the high bias case. The low bias case for the textbook specimens is likely fixed since the measurements were made on pristine fracture surfaces using state-of-the-art digital imaging technology. However, the precision for the high bias case can be improved in the future with the development of better procedures for interpretation of the fracture surface features, including the E 23 recommendations given in this paper, to reduce bias between operators. Further improvements

can be realized in the future by using SFA results determined from instrumented striker data to check the digital analysis results.

Our study has also led to the conclusion that the widely used photograph comparison method is neither accurate, nor precise and should be abandoned for quantitative measurements. In particular, the results for the photograph comparison method on the "textbook" specimens gave an average difference between the digital imaging result and the photograph comparison method of 19.6 % shear, with the largest deviation being 55 % shear. This alone is sufficient to demonstrate that the photograph comparison method is inaccurate and imprecise. However, the LES round robin even more dramatically demonstrates the limitations of the photograph comparison method. Variations as large as 70 % shear were reported on individual specimen measurements, and the average maximum to minimum deviation of the 5 participants over the entire range of 87 specimens was 41.9 % SFA.

Recommendations for changes to the E 23 standard have been made. These proposed changes will make measurement of percent shear for typical specimens more clearly defined and will give the user of the standard better guidance on the error to be expected for the various methods. In addition, changes to the standard to address fracture surface features not currently anticipated by the current standard must be included.

The general conclusion from this work is that SFA can be accurately measured and should be considered as a useful Charpy parameter. In typical Charpy specimen applications, accuracies of about 1 % to 5 % shear area should be expected. Arguments have been put forward in support of the idea that the SFA parameter, and the FATT index, are more fundamental and physically based for the determination of the safe temperature for operation of structures and components than an energy based parameter and index such as 30 ft-lbs.

Acknowledgements

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5. Tests of Met's, Vol. I, 1881, pp 122-146, 212-222, "Results of impact tests of various grades of wrought iron with photographs of fractures.
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7. Bibliography of Impact Testing, September, 1925, White, A.E., Clark, C.L.
8. ASTM E23-07, "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials".
9. Dixon, B.F., "Reliability of Fracture Appearance Measurement in the Charpy Test", Welding Journal, August 1, 1994.
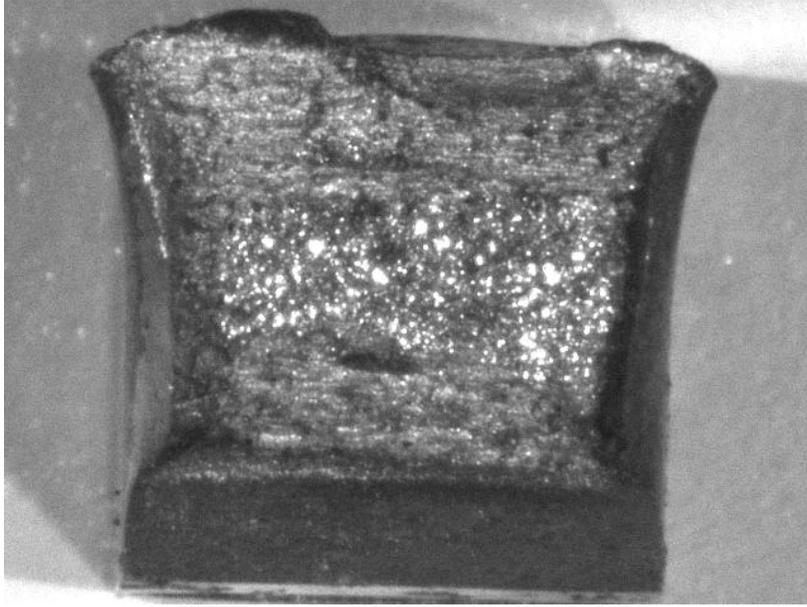
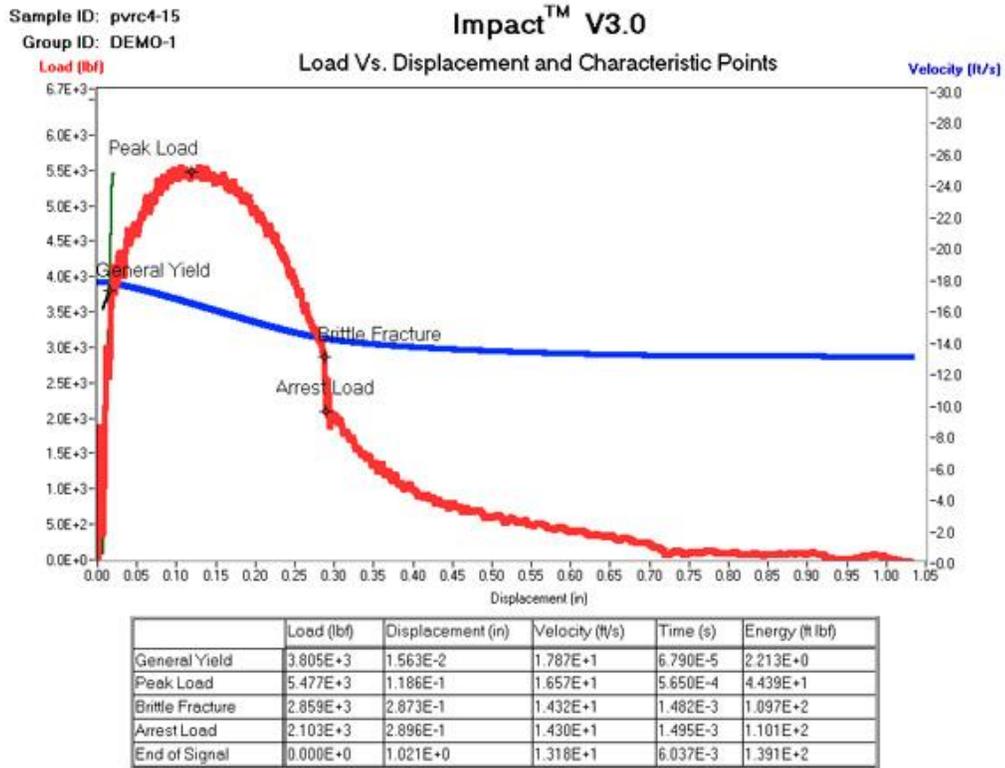**Figure 1 Textbook Fracture Surface Showing Bright Shiny Faceted Region Surrounded by Ductile Fracture Area.**

	Load (lbf)	Displacement (in)	Velocity (ft/s)	Time (s)	Energy (ft lbf)
General Yield	3.805E+3	1.563E-2	1.787E+1	6.790E-5	2.213E+0
Peak Load	5.477E+3	1.186E-1	1.657E+1	5.650E-4	4.439E+1
Brittle Fracture	2.859E+3	2.873E-1	1.432E+1	1.482E-3	1.097E+2
Arrest Load	2.103E+3	2.896E-1	1.430E+1	1.495E-3	1.101E+2
End of Signal	0.000E+0	1.021E+0	1.318E+1	6.037E-3	1.391E+2

Figure 2 Example of an Instrumented Striker Signal for a Charpy Test Conducted in the Transition Region, Showing Sudden Drop in Load Associated with Brittle or Fast Fracture Event.

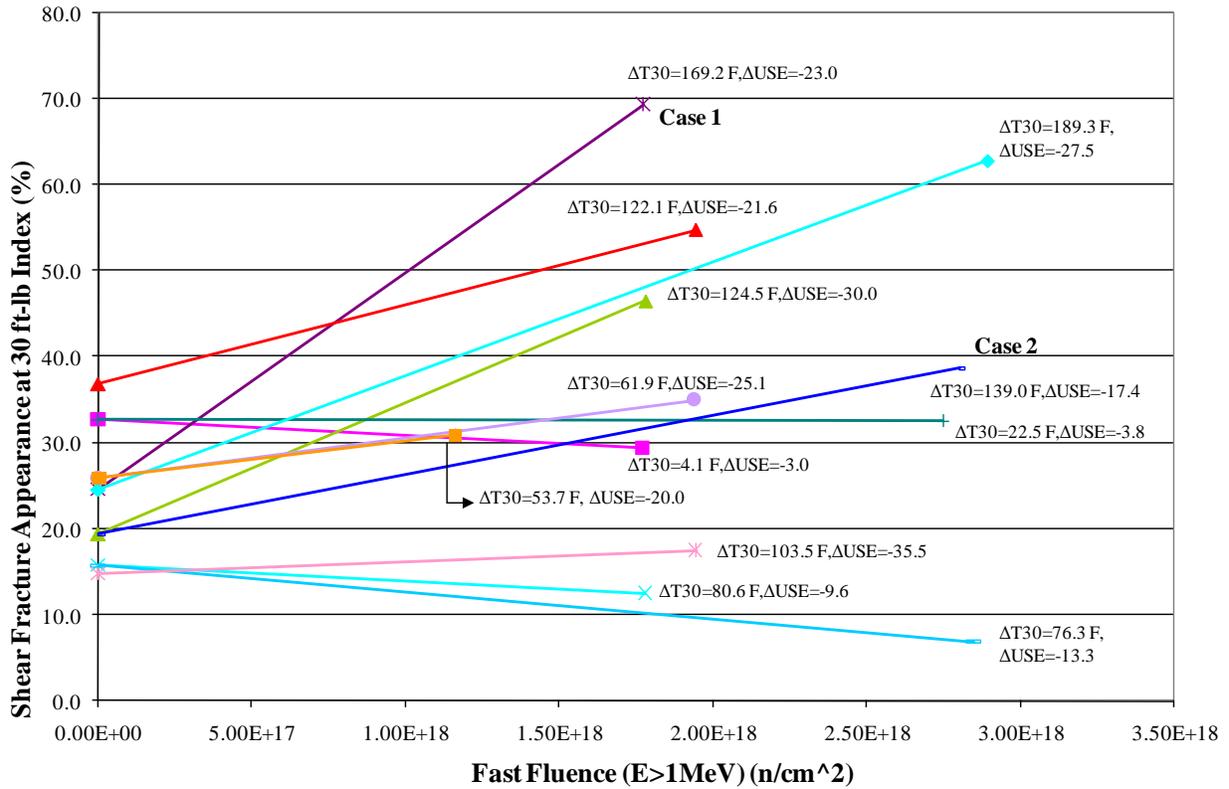**Boiling Water Reactor Surveillance Data**

Figure 3 Plot of SFA at 30 ft-lb as a Function of Fast Neutron Fluence for Irradiated Welds. Note that the Charpy Shift Measured at the 30 ft-lb Index does not Increase Proportionally with SFA.
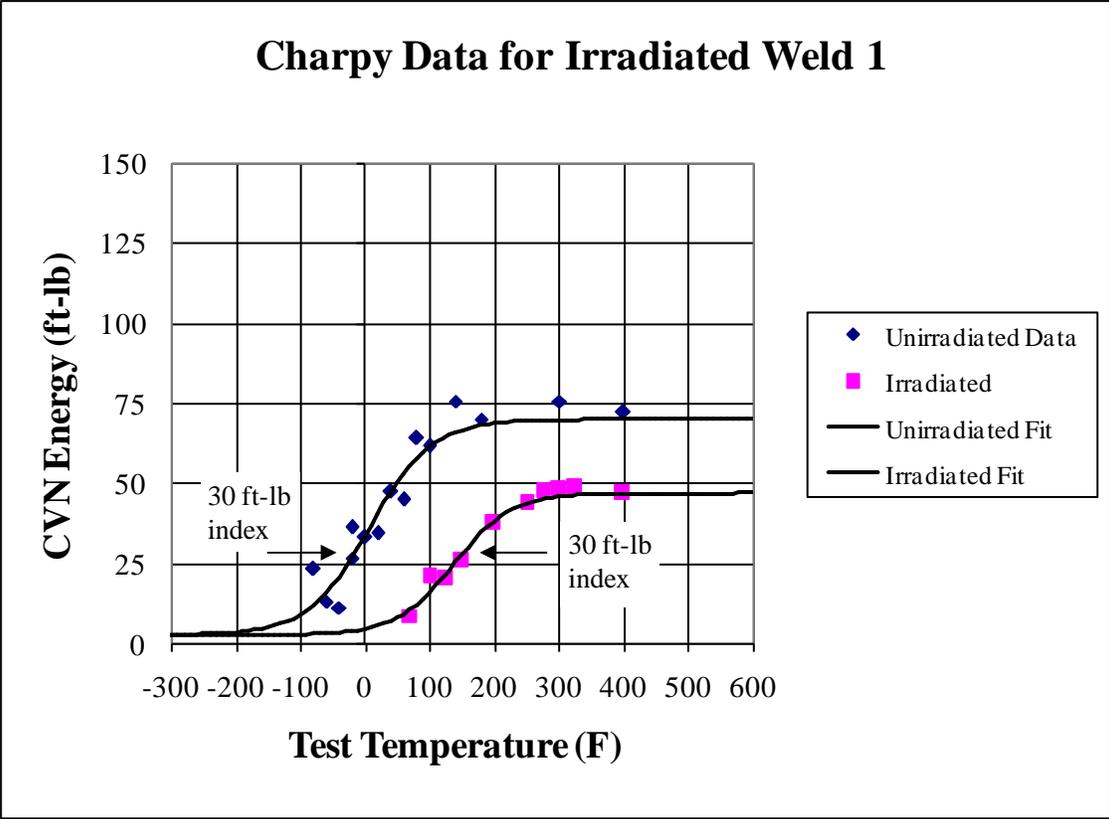
Figure 4 Plot of the Case 1 Charpy Energy-Temperature Curve. For this Material, the Change in Slope Results in a Large Change (~45%) in SFA at the 30 ft-lb Index.
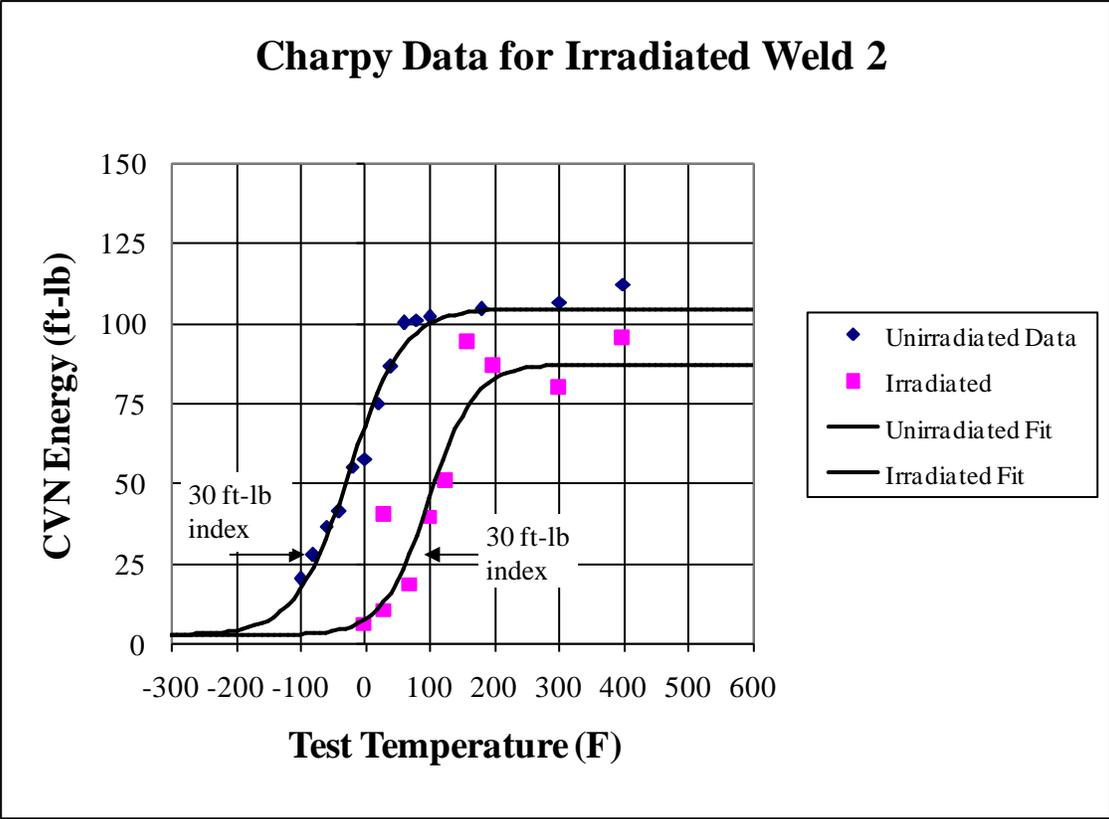
Figure 5 Plot of the Case 2 Charpy Energy-Temperature Curve. For this Material, the Change in Slope Results in Only a Modest Change (~18%) in SFA at the 30 ft-lb Index.

Figure 6 Image Acquisition and Analysis Hardware for Accurate Percent Shear Measurement.
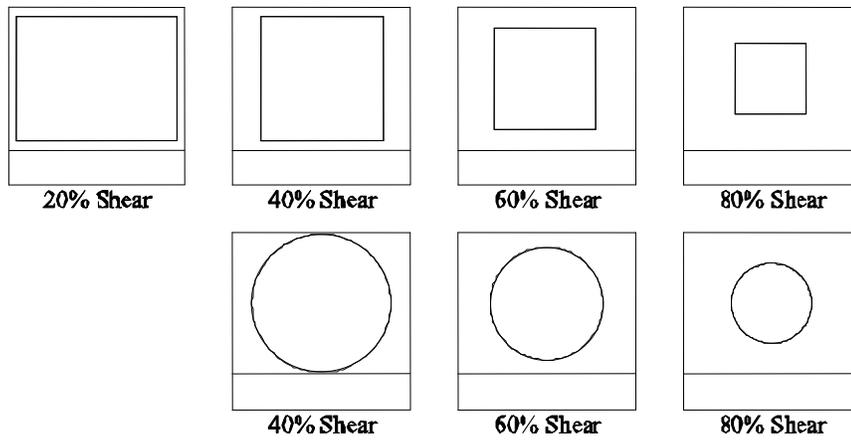
Figure 7 Enlarged Image of CAD Drawings used for Precision Study.

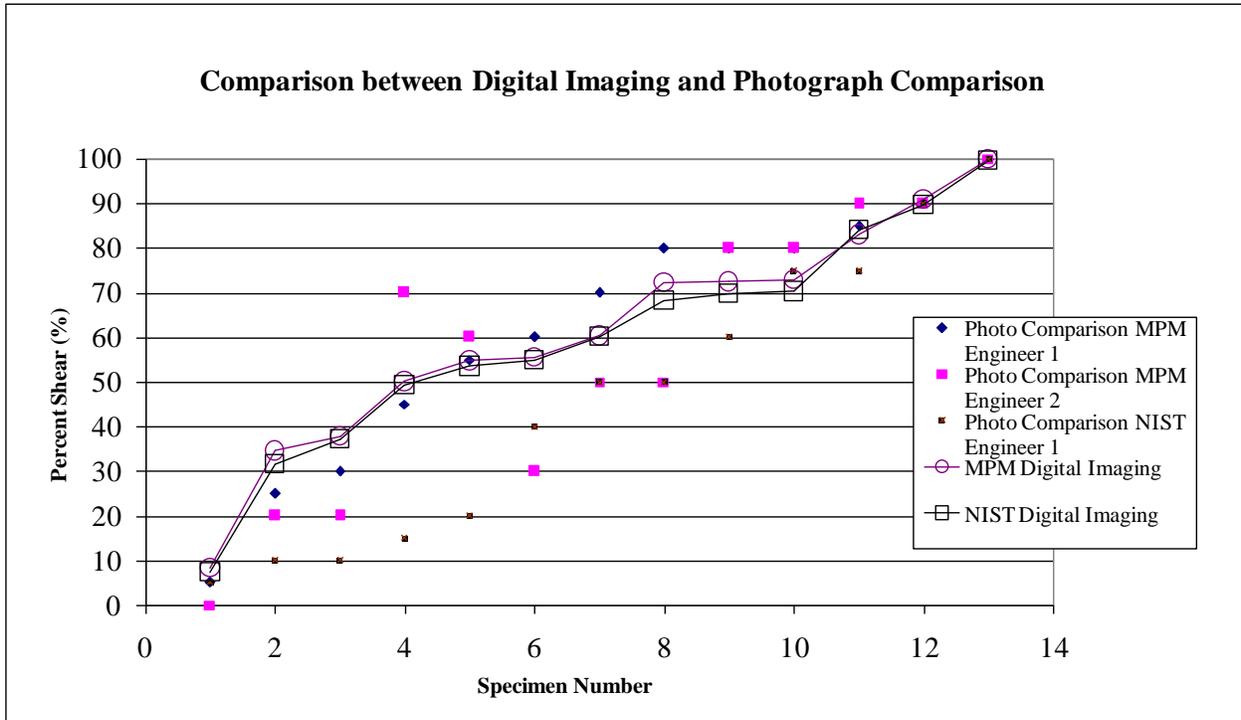**Comparison between Digital Imaging and Photograph Comparison**

Figure 8 Comparison of Percent Shear Data Obtained Using Digital Imaging with Results Obtained Using Photograph Comparison Method.
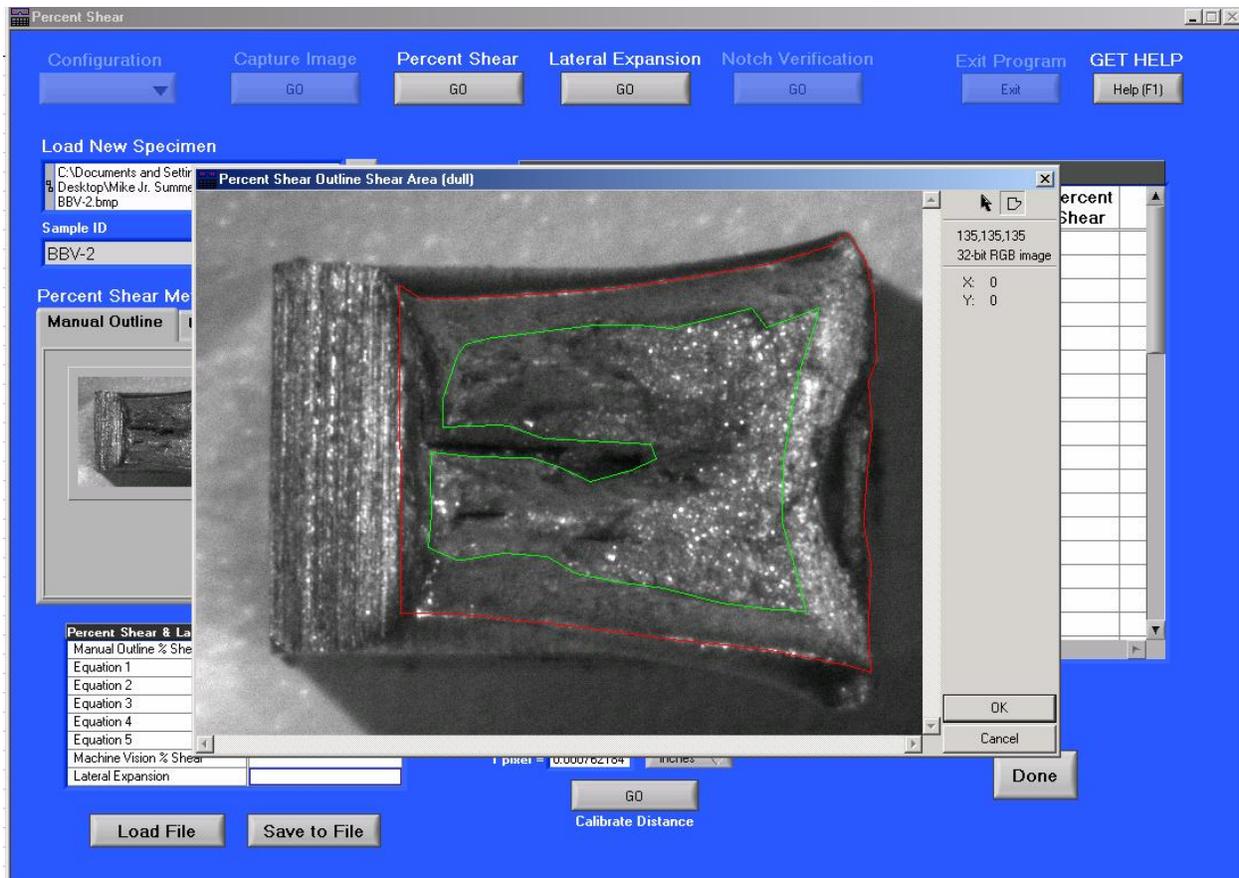
Figure 9 Example Showing Outlines for the Brittle and Total Fracture Areas for a Test Specimen with a Large Crack Normal to the Primary Plane of Fracture.
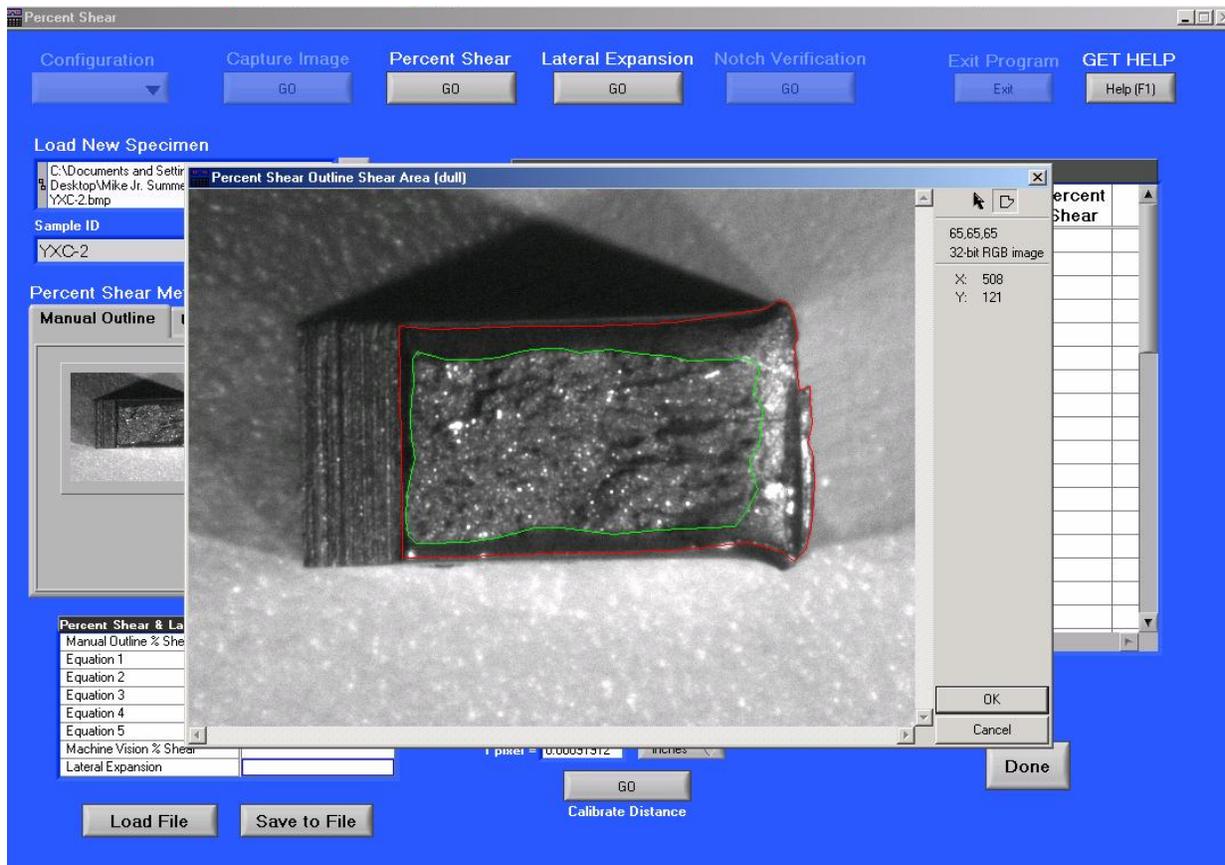
Figure 10 Example Showing the Outlined Brittle and Total Fracture Areas, for a Sample Having a Flat Fast Fracture Region Lacking Clear Brittle Facets Throughout.

MPM & NIST Data for Lake Erie Steel
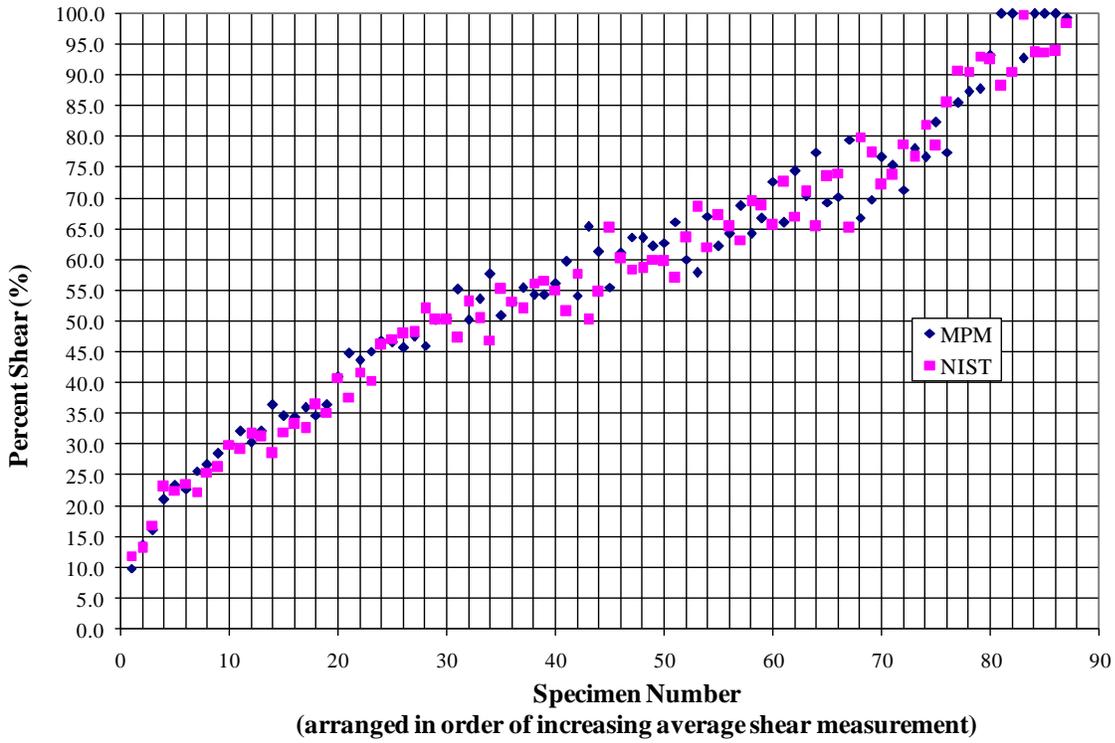**Round Robin**

Figure 11 Comparison of Round Robin Percent Shear Data Obtained by NIST and MPM using Digital Imaging Technology.
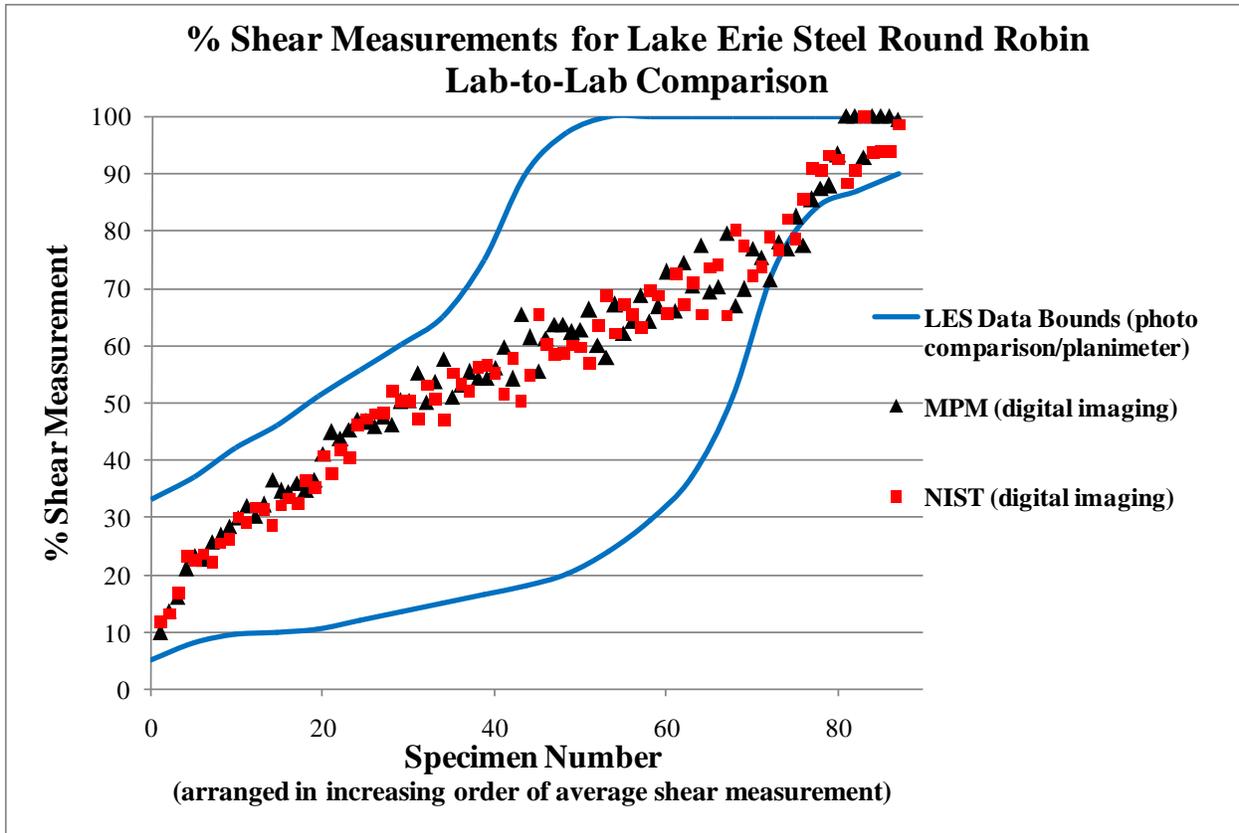
Figure 12 Comparison of Data from the LES Round Robin with Results using Digital Analysis Technology from this Study. The Round Robin Data were Collected using Photograph Comparison and Planimeter Methods.

Table 1 Area Measurements Made Using a Calibration Reticle.

	Precison Reticle Area (in^2)	
	Non-technical Assistant	**Trained Engineer**
Target Value	**0.0400**	**0.0400**
Measured Average	0.0400	0.0400
% Difference	0.0631	0.0193
Std Dev	3.479E-05	1.131E-06

Table 2 Percent Shear Data Measurements Made on CAD Drawings using Digital Imaging System.

Trained Engineer 1

	Percent Shear - Square				Percent Shear - Round		
Target	**20.0**	**40.0**	**60.0**	**80.0**	**40.0**	**60.0**	**80.0**
Average	20.9	40.4	60.1	79.5	41.1	60.2	79.8
Std Dev	0.249	0.309	0.082	0.047	0.170	0.170	0.082

Trained Engineer 2

	Percent Shear - Square				Percent Shear - Round		
Target	**20.0**	**40.0**	**60.0**	**80.0**	**40.0**	**60.0**	**80.0**
Average	20.2	39.8	59.5	80.1	40.1	59.8	79.9
Std Dev	0.090	0.073	0.051	0.045	0.232	0.093	0.194

Non-technical Staff Member

	Percent Shear - Square				Percent Shear - Round		
Target	**20**	**40**	**60**	**80**	**40**	**60**	**80**
Average	20.00	40.00	59.60	80.30	40.53	60.43	80.27
Std Dev	0.0816	0.0816	0.0000	0.0816	0.0471	0.0943	0.0471

Table 3 Percent Shear Data Measurements Made on Textbook Specimens with Clearly Defined Brittle Fracture Areas using Digital Imaging System.

Specimen	MPM Percent Shear (%) Digital Imaging Software	NIST Percent Shear (%) Digital Imaging Software	Difference in Percent Shear (%)
1	100.0	99.7	0.3
2	60.3	60.2	0.1
3	83.0	84.1	1.1
4	72.5	69.8	2.7
5	72.2	68.2	4.1
6	90.9	89.7	1.2
7	54.8	53.5	1.3
8	55.6	54.9	0.7
9	72.9	70.3	2.6
10	37.8	37.3	0.5
11	50.1	49.3	0.8
12	34.6	31.6	3.0
13	8.3	7.4	0.9

Table 4 Percent Shear Data Measurements Made on Textbook Specimens with Clearly Defined Brittle Fracture Areas using Photograph Comparison Method.

	Average Percent Shear (%) Digital Image	Percent Shear (%) Photo Compare Engineer 1	Percent Shear (%) Photo Compare Engineer 2	Percent Shear (%) Photo Compare Engineer 3	Maximum Difference (%) Photo Compare/ Digital Image
1	99.9	100.0	100.0	100.0	0.0
2	60.2	70.0	50.0	50.0	20.0
3	83.6	85.0	90.0	75.0	15.0
4	71.2	80.0	80.0	60.0	20.0
5	70.2	80.0	50.0	50.0	30.0
6	90.3	90.0	90.0	90.0	0.0
7	54.2	55.0	60.0	20.0	40.0
8	55.2	60.0	30.0	40.0	30.0
9	71.6	80.0	80.0	75.0	5.0
10	37.6	30.0	20.0	10.0	20.0
11	49.7	45.0	70.0	15.0	55.0
12	33.1	25.0	20.0	10.0	15.0
13	7.9	5.0	0.0	5.0	5.0