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ABSTRACT

The confident application of miniature tensile specimens requires adequate control over their fabrication and is facilitated by automated test and analysis techniques. Three fabrication processes -- punching, chemical milling, and electrical discharge machining (EDM) -- were recently evaluated, leading to the replacement of the previously used punching technique with a wire EDM technique. The automated data acquisition system was upgraded, and an interactive data analysis program was developed.

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INTRODUCTION

Design of the structural components of nuclear reactors requires knowledge of the changes in strength and toughness that occur during irradiation at elevated temperatures. In order to supply design or surveillance data from limited experimental irradiation volumes, it has often been necessary to use miniaturized specimens. One of the smallest specimens currently used for determination of tensile properties is a sheet-type specimen 12.7 mm long and 0.25 mm thick.[1] Miniature specimens such as this have been a mainstay of the fusion materials program for many years and will continue to be used extensively in future research.

Periodic review and improvement in the fabrication, testing, and analysis techniques are necessary to ensure that such specimens continue to produce valid data. The specimens were originally developed to be punched from sheet stock that had been rolled to the desired specimen thickness. The primary advantages of this technique were its rapidity and its low cost.[1] Specimens were fabricated on site without the delays associated with using an offsite vendor or the expense of machining or tooling up for each production batch.

The main disadvantage of fabrication by punching is that the act of punching produces unavoidable deformation in the specimen; even under optimum conditions, the best specimens are likely to exhibit some cupping. Although such problems are worst in very soft or very tough materials, their effects can frequently be ameliorated by performing the required heat treatments after the punching operation. Despite some difficulties with punched specimens, it was possible to generate reproducible results for the changes in tensile behavior caused by irradiation,[2] particularly when punching was coupled with a polishing operation to deburr the specimens.

To produce good specimens consistently, the punch and die must be kept sharp. In addition, the clearance between punch and die must be appropriate for the material being punched. If the punch clearance and sharpness are not optimum, the cupping can be more severe and a burr will remain that must be polished away. Punches can be sharpened only a limited number of times and are subject to damage during handling. The choice of punching for specimen fabrication was therefore reevaluated. Two other techniques were considered potentially feasible on the basis of both cost and ease of fabrication: chemical milling and electrical discharge machining (EDM).

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[1]Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

Chemical milling is a photo-chemical etching technique that is frequently used to make high precision components for a number of industries, and was attractive due to its low cost and relatively rapid turnaround time for the production of large numbers of specimens. It entails masking the surface, stripping the mask from the areas to be etched away, chemically etching away the undesired regions, and removing the mask. While part outlines can be achieved with a large degree of accuracy, the edges eaten away are known to be somewhat uneven and undercut, depending on material, shape, size and thickness.

EDM is the most expensive of the three techniques on a per-specimen basis, but held the most promise for distortion-free, reproducible specimens. EDM is a means of shaping conductive materials by arc erosion. It is particularly well suited to cutting internal shapes and delicate pieces. A tool is held a small distance from the workpiece while an electrical input builds up a charge and raises the voltage across the gap between the two, which is filled with a dielectric fluid. When the potential reaches a certain level, a discharge occurs between the closest points on the two surfaces. A minute amount of metal is melted and expelled in a globular form where the spark strikes the workpiece, leaving a small crater. This is repeated 20,000 -- 300,000 times per second with the spark positioned by a servo-control device.

Control specimens, used for verification of the test system operation at the start of each testing sequence, were originally punched from solution annealed 304 stainless steel. The fabrication of new control specimens was used as a convenient means of evaluating fabrication techniques. The specimen dimensions are shown in Figure 1.

The automation of both data acquisition and analysis were of interest for a number of reasons, including the elimination of human error that can occur during the manual analysis of tensile charts. In addition, automated analysis makes it easier to compare data from different specimens by making it possible to plot data at the same scales. Earlier unsuccessful efforts at automated analysis attempted to build in sufficient judgement that the computer could determine the major tensile properties without user involvement. The current effort focussed on a more flexible, user-interactive analysis, that left all interpretation of the tensile chart in the hands of the user.

EXPERIMENTAL PROCEDURE

Specimen fabrication technique

Two punch and die sets of hardened D2 tool steel were obtained to allow consideration of different clearances that might be appropriate for different materials of interest. Tolerances of 0.3 and 1.0 mils were selected for the two sets. The set with the larger clearance was used to punch specimens from the same sheet of 304 stainless steel that had been used to punch the earlier control specimens. Punched specimens were used in an as-punched condition because the polishing operation typically used to deburr the miniature tensile specimens is known to remove some of the artifacts of punching that were of interest here; polishing the specimens in this case therefore have introduced additional variability.

The original drawing specified a width of 40 mils +1.0/-0.0 mils. Only one company of the several contacted (Hutchinson Technology in Hutchinson, MN) was willing to make chemically milled specimens on a prototype basis, and then only after the tolerance on the gauge width was increased to +1.5/-0.0 mils. Due to a paucity of the original 304 stainless steel sheet stock, only a small number of chemically milled specimens were made from the original solution annealed sheet stock. A number of additional specimens were made from vendor-supplied 304 stainless steel to investigate more thoroughly the viability of the fabrication technique. The vendor indicated that the vendor-supplied 304 was in a "fully hardened" condition.

A wire EDM process was used to fabricate specimens at JW Industries of Albuquerque, NM, who claimed that dimensions could be held to within 0.2 mils. Specimens were made only from the original 304 sheet stock. In anticipation of the success of the EDM technique, enough specimens were made to provide control specimens for a number of upcoming test sequences.

Three types of examinations were performed on each specimen type to determine the effect of production process on the quality of the specimens. The gauge dimensions were measured to determine the gauge measurements that would typically be used for calculation of cross sectional area in tensile tests. Optical microscopy was performed on transverse specimen sections to determine 1) whether there was evidence of microstructural change at the specimen edges, and 2) the variability in specimen cross section associated with each technique. Quantitative evidence for material distortion was obtained by comparing Knoop hardness measurements taken on the transverse specimen sections at both the cut edge and in the body of the specimen.

Tensile tests were performed on each specimen type to determine the effect of production process on the subsequent tensile data. The variability of the tensile data was evaluated for each production process.

Automation

Data acquisition was automated with the assistance of a National Instruments LAB PC board installed in an IBM PC/AT computer. The board was programmed in Quick Basic using the LABWINDOWS software system, also from National Instruments. It provides multichannel, double buffered, analog input over a 10 volt range (±5V), with a maximum single channel acquisition rate of up to 62.5 Khz. The output of the load cell and LVDT transducers, which range over ±10V, is fed through a simple voltage divider to reduce it to the range of the LAB PC board. Each output line includes a capacitive filter to minimize the fluctuations in the signal due to electrical noise.

Data are acquired on two channels at sampling intervals ranging from 0.25 to 3 seconds. With a maximum of 4000 data points available per channel, the maximum test length over which data can be obtained at a 0.5-second sampling interval, for example, is 33 minutes. To assure that all test data are acquired, data acquisition is begun just before a test is started, and continues until shortly after the specimen fails. A real-time display of the data is provided on the PC monitor, which shows the test trace graphically as well as the corresponding values of load and displacement in terms of both transducer voltage and the physical units of pounds and inches. In the event of a computer failure, a backup chart recorder output is also generated during the test.

An interactive program for analysis of the tensile data was also written in Quick Basic. It provides numerous options to edit and smooth the data at the discretion of the user prior to calculating the tensile properties of interest. The user chooses the slope of the straight line used to define the elastic portion of the trace. The user also has the freedom to accept or change the locations at which the program calculates the standard tensile values.

The data acquisition and analysis program was used to analyze the results of 56 tests performed on specimens irradiated to low doses in the Los Alamos Spallation Radiation Effects Facility (LASREF). The irradiation experiment is described in detail in reference 4. The specimens were made from both relatively strong and soft materials, including 316 stainless steel and several copper alloys. Yield strengths ranged from about 25 to 600 MPa, while ultimate strengths ranged from 150 to 700 Mpa. The corresponding ductilities ranged from 0 to 55%.

RESULTS

Specimen fabrication technique

Dimensional measurements. Three measurements each of the gauge thickness and width were obtained (using a digital micrometer accurate to 0.05 mils) on five specimens produced by each technique. The contact surfaces of the micrometer were a cone point and a knife edge, which allowed accurate thickness measurements to be made even on the punched specimens. The cone point was placed inside the punched "cup" while the knife edge was placed on the convex specimen surface to eliminate any potential distortion in the measurement caused by the burr. The average dimensions and their variability are given in Table 1.

It is evident that while punching produced the most uniform measurements of specimen width, it also gave rise to the largest variability in measured gauge thickness, presumably due to the cupping of the specimen during the punching operation. Conversely, chemical milling produced the least distortion in the measured specimen thickness but the largest variability in gauge width. The latter result arises because chemical milling is accomplished by photographically etching the sheet stock from both sides, producing a slight bevel from each surface to the center of the sheet thickness. It is worth noting that the variability in width produced by chemical milling is more significant for hardened steel than for solution annealed steel, most likely because the larger stored energy of the hardened steel increases the nonuniformity of the etching process.

Optical metallography. The same five specimens of each type that were used for the dimensional measurements were sectioned, mounted, and polished to reveal a transverse section through the gauge section. Figure 2 shows the appearance of the edges on the transverse sections for each fabrication process. The punched edges shown in Figure 2a are obviously somewhat deformed, although they are not in need of deburring, demonstrating that the clearance between the punch and die is reasonable for the 304 steel. The chemically etched specimens exhibit a wavy, nonuniform surface that appears to be more variable in the solution annealed specimens (Figure 2c) than in the hardened specimens (Figure 2d). This observation is consistent with the tendency of finer-grained materials to etch more smoothly.[3] The EDM specimens shown in Figure 2b exhibit a relatively good squared-off edge with a minimal amount of what is probably nonadherent debris in the vicinity of the edge. Such debris can result when material at the melted edge of the specimen does not fall away from the specimen completely. The debris was more visible when the metallographic mount was examined under the microscope than it is in the photograph. Neither the chemically milled nor the EDM specimens show evidence of microstructural change at the machined edges.

Hardness measurements. Knoop hardness was measured (using a 200 gram load) on the transverse metallography sections at both a specimen edge and the specimen center. Two measurements were made on each specimen at each location. The average hardness values are given in Table 1. The hardness measurements are almost identical at the edges and centers of the annealed specimens produced by chemical milling and by EDM. It is evident that the punching operation severely deformed the microstructure at the edges of the specimens, even for the relatively good specimens that were produced with the new punch and die. The punching operation also caused the hardness in the center of the annealed specimens to increase slightly relative to the center of the specimens produced by the other two techniques. It appears from the data that both EDM and chemical milling cause a small difference in hardness between the center and the machined edge. The reason for this decrease is not immediately obvious, although it is probably related to the relaxation of the microstructure allowed by the melting or etching that occurred at the specimen edges.

Variability in cross sectional area determination. Strength calculations require an accurate determination of the cross sectional area of a specimen. Some error is typically associated with standard measurement techniques applied to punched specimens, given the tendency for such specimens to become cupped during punching and the potential nonuniformity of the deburring operation that usually follows punching. Several types of area calculations were performed to assess both the variability in the actual cross sectional area and the validity of the standard area calculation (i.e., the product of measured thickness and width) for each fabrication technique.

Photomicrographs at 100x of the transverse specimen sections shown in Figure 2 were xeroxed to enlargements of 150x. Cut-outs from the xerox paper corresponding to the cross sectional area at the maximum measured width were weighed and compared to cut-outs corresponding to the actual cross sectional area. The average percentage difference between the two represents the deviation in area, ΔA_o, that would occur for area calculations using the dimensional measurements obtained prior to a tensile test, assuming that the measurement device contacts the points of greatest thickness. These deviations are also given in Table 1. The largest error in cross sectional area was obtained with punched specimens, while the least was obtained with EDM specimens. The error in cross sectional area associated with chemical milling was intermediate, and was virtually the same for solution annealed or cold worked material. If the area deviation were large, as is the case for the punched specimens, the value $1-\Delta A_o$ could be used as a multiplicative normalization factor that might provide a better determination of cross sectional area than that calculated directly from the dimensional measurements, if a value for ΔA_o were obtained for each batch of specimens fabricated.

Tensile data. Tensile tests were performed on five specimens of each type. A nominal gauge length of 0.2 inches was assumed for all specimens. The tensile data are given in Table 2. While the ultimate strength of the punched specimens is almost identical to that of the EDM and chemically milled specimens, the yield strength is about 15% higher and the ductility is significantly lower.

The values of gauge width and thickness were determined for each specimen as the average of three measurements each. The measurements were performed between ball surfaces in an LVDT device that was generally used to obtain such measurements. The dimensions obtained in this manner were not consistent with those obtained with the cone point and knife edge micrometer, and exhibited more variability as well. The width measurement was particularly difficult to obtain between ball surfaces since the positioning is not stable and requires continuous operator contact, an undesirable condition with irradiated specimens. For these reasons, although the ball surfaces were used for the measurements on these specimens, the use of the ball surfaces for dimensional measurements was discontinued for future testing and replaced with a conventional micrometer.

Automation

The data acquisition system is quite reliable and reproducibly generates the error-free data files required by the data analysis program. The voltage dividers and capacitive filters consistently produce data in the ±5V range with very low noise levels. The voltage signals typically fluctuate by about ±0.048 volts, which corresponds to about ±0.48 pounds and ±0.000048 inches on the load cell and LVDT, respectively. Data acquisition is sensitive to other activities occurring on the same lab bench during testing; care must therefore be taken to limit simultaneous activities.

The data obtained on the LASREF specimens are reported in reference 4. Extraneous data acquired before the test started and after the specimens failed were easily deleted. The curves were typically averaged from one to four times to obtain smooth curves in which linear elastic portions were easily defined. The tensile values calculated using the automated user-interactive program were compared to the values determined by manual analysis of the charts. The values of strength and elongation determined by using the program were generally quite consistent with the values determined manually (Figure 3), but they were calculated much more quickly and actually provided better data in several cases where the axis scale chosen for the chart recorder produced highly compressed charts.

DISCUSSION

Specimen fabrication technique

The measured widths given in Table 1 are all within the specifications of the drawing shown in Figure 1. In the worst case, a 1% variability in the thickness was introduced during the punching operation. From a dimensional standpoint alone, therefore, all three of the fabrication techniques could be considered acceptable. The punched specimens produced in this experiment, however, are known to be superior in quality to others produced more typically (see Figure 4),[2,5] in that they exhibited virtually no cupping or burring. In addition, the clearance between the punch and die is not necessarily appropriate for other alloys, and continued use of punching for specimen production would require some effort at optimization of the clearance for a range of alloys. It is likely that the dimensional quality of punched specimens would degrade with time in a way similar to that observed previously. The necessary addition of a polishing operation to deburr punched specimens, as has been done previously, would introduce even more variability in specimen dimensions due to the difficulty of uniformly and reproducibly deburring specimens. Thus punching the specimens was considered the least desirable option from the standpoint of dimensional control and reproducibility.

If the sharpness of the punch and the clearance between punch and die are not optimized, the edges of the specimens can crack or be deformed excessively, potentially invalidating the tensile results. Cracked specimens can lead to premature failure,[2] while smeared edges represent regions of different microstructure with potentially different tensile behavior.[3] While annealing treatments applied after the punching operation can restore the microstructure of specimens deformed during punching, smeared specimens tend to cup excessively when they are punched, resulting in nonuniform cross sections.

Post-fabrication heat treatment has been successful at removing the effects of deformation: in the PE16 specimen shown in Figure 4a, no difference in hardness was observed after heat treatment between the specimen edge and center, despite the obvious band that remained as an artifact indicating the size of the sheared zone produced during the punching operation.[3] The burr that existed prior to polishing in these specimens is shown in Figure 4b. Punching soft materials can also lead to significant nonuniformity in the specimen cross section; Figure 4c shows a deburred specimen of Marz copper with large differences between the two curved edges. The nonuniform, non-square edges shown in the specimens in Figure 4 can lead to errors in cross sectional area determinations of up to several percent.

The metallography shown in Figures 2 and 4 and the hardness and tensile data given in Tables 1 and 2 demonstrate that punching is likely to alter the structure at the edges of the specimens. Punching could therefore only be considered acceptable if the specimens produced were heat treated following fabrication to remove the deformation remaining at the specimen edges after punching.

It is difficult to assess the effects of cracks that can be produced at the specimen edges; certainly it is impossible to remove them after they are introduced. One example of such cracks, produced in specimens of A212B, is given in Figure 5 (before deburring).[2] While such cracks do not typically lead to errors in the determination of cross sectional area, they are likely to lead to premature fracture of the specimen.

The condition of the 304 sheet stock supplied to the vendors by PNL was not known precisely; the sheet stock was initially believed to be in a slightly cold worked condition on the basis of tensile data obtained previously from miniature tensile specimens punched from the same sheet. The current data were evaluated to determine whether this belief was correct. The variability in the tensile data on the 304 specimens was assessed in terms of equivalent cold work level using Figure 6 as follows: Trend lines were drawn through the strength data provided in references 6 and 7 as a function of cold work level. Only minimum values from the ASTM specification were available for the solution annealed condition (i.e., 0% cold work level). No information on variability was available for these data. The tensile values from the current experiment were then located on these trend lines; an equivalent cold work level was extracted as the abscissa coordinate corresponding to the yield strength on the trend line. The equivalent cold work values are given in Table 2. Error bars are shown only for those cases where the error was larger than the size of the data point itself. The fact that the ultimate strengths were somewhat higher than would be expected for the cold work level that was determined is consistent with the observations of earlier experimenters.[1]

The tensile data generated in this experiment indicated that the sheet stock provided by PNL was probably nominally in the solution annealed condition. The yield strength data from the EDM and chemically milled specimens suggest that the 304 sheet stock supplied by PNL was in a solution annealed condition, since the value given for the 0% cold work level in Figure 6 is merely the ASTM specification for the minimum strength of 304 stainless steel. The tensile data on the new punched specimens imply that punching even the best quality 304 specimens that are achievable induces the equivalent of about 1% cold work, whereas the data on the old punched specimens imply that the punching process previously in use more typically induced the equivalent of about 5% cold work. In addition, more scatter was observed in the tensile data generated from punched specimens than from EDM or chemically milled specimens. Similar behavior is undoubtedly exhibited by other materials, particularly when the punch and die clearances are not optimized.

The final factor to be considered in the selection of an improved fabrication process was cost. Punching is obviously the cheapest if no optimization of punch and die clearances is explored, but the optimization that should be explored with this technique has the potential for being quite costly in both dollars and man-hours. It should be possible to punch specimens from any material and produce specimens of the same quality as was obtained in the current work if the clearances are optimized. The cost for EDM specimens depends on the number of specimens being made, but appears to be roughly \$10 each. Chemical milling involved a set-up charge of about \$500 and would cost about \$500 for each future batch of specimens for lots of up to 1000 specimens. Since only small numbers of these specimens are typically manufactured at any one time, the cost savings potentially available with chemical milling would not be realized, and this process would conceivably be more expensive than the EDM technique. Thus the technique selected for the fabrication of all future miniature tensile specimens is EDM.

Automation

The use of the automated user-interactive analysis program speeds up the analysis of tensile data significantly. Data from a single test can be completely analyzed in about 10 minutes. This is a considerable improvement, particularly for those cases where manual interpretation of chart recorder output is not straightforward.

The automated determination of yield strength was typically within about 10 MPa of the manually determined yield strength. Larger deviations were observed only for highly compressed charts, which occurred only for specimens that were stronger than expected. The difference between the two types of ultimate strength values was much smaller, typically less than 5 MPa, irrespective of the magnitude of the ultimate strength. This reflects the relative ease with which a maximum value can be chosen on a chart trace.

The automated determination of uniform elongation was generally within about 1% of the value determined manually. Larger differences were observed for those specimens that exhibited a long plateau at the maximum load, where it is difficult manually to pick out on a chart trace precisely the location of maximum load. The two types of total elongation values were typically within 2% of each other. The larger variability is attributed to the difficulty of establishing on a chart trace exactly when a specimen fails.

CONCLUSIONS

After three fabrication processes (punching, chemical milling, and EDM) were evaluated, the EDM technique was selected for future fabrication of miniature tensile specimens. This choice was based on an evaluation that included dimensional inspection and optical metallography as well as hardness and tensile measurements. The automated data acquisition system was upgraded, increasing its reliability and minimizing the magnitude and frequency of electrical noise, and an automated, user-interactive data analysis program was developed to facilitate the analysis of the tensile data.

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FIGURES

1. Dimensions of miniature tensile specimen.

2. Transverse sections showing specimen edges for each fabrication type at 100x, ordered by decreasing edge quality: (a) punched, (b) EDM, (c) chemically milled (PNL-supplied material), and (d) chemically milled (vendor-supplied material).

3. Comparison between tensile values calculated manually and using the automated analysis program; the "delta" was calculated in each case by subtracting the manually determined value from the value determined using the analysis program: (a) yield strength, (b) ultimate strength, (c) uniform elongation, and (d) total elongation.

4. (a) and (b) Miniature tensile specimen of PE16 showing (a) band delineating the size of the sheared zone that resulted from punching, (b) the degree of cupping that lead to the sheared zone. (c) Marz copper specimen showing nonuniformity of curved edges.

5. Cracks produced during punching of miniature tensile specimens of A212B pressure vessel steel.

6. Assignment of equivalent cold work levels for test specimens relative to strengths given in References 6 and 7.

TABLE 1
AVERAGE DIMENSIONS, HARDNESS AND CROSS SECTIONAL AREA
OF MINIATURE TENSILE SPECIMENS

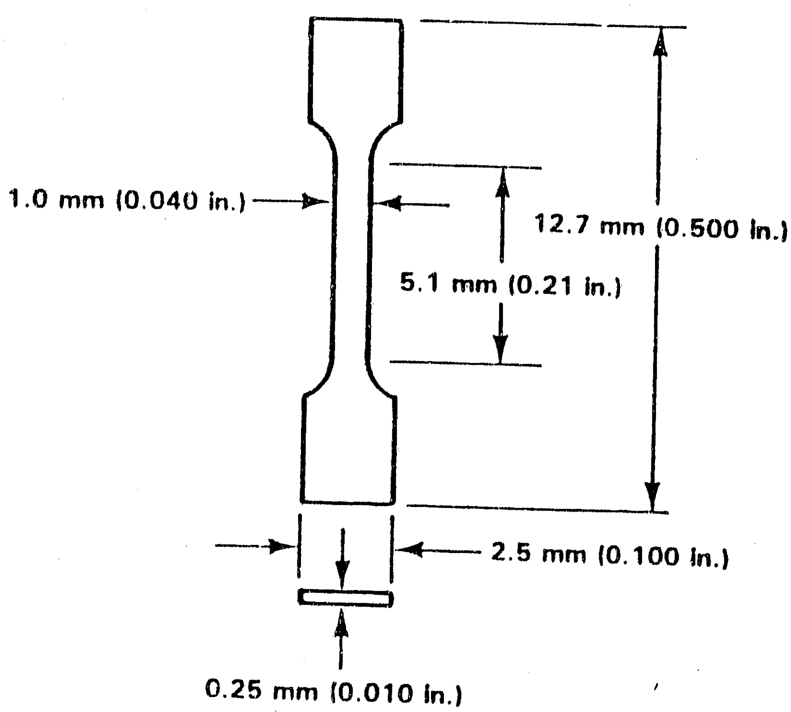
Production Process	Dimensions		Hardness		Deviation in cross sectional area (%)
	Thickness (mils)	Width (mils)	Edge (KHN)	Center (KHN)	
PNL-supplied material (solution annealed 304 stainless steel)					
Punching	10.20 ± 0.10	40.45 ± 0.05	357 ± 18	173 ± 5	3.8 ± 1.6
EDM	10.45 ± 0.05	40.75 ± 0.10	157 ± 8	163 ± 2	0.8 ± 0.4
Chemical milling	10.25 ± 0.05	40.35 ± 0.20	151 ± 5	161 ± 4	1.4 ± 0.9
Vendor-supplied material (hardened 304 stainless steel)					
Chemical milling	9.90 ± 0.05	40.65 ± 0.25	402 ± 9	428 ± 9	1.7 ± 0.4

TABLE 2
AVERAGE TENSILE DATA DETERMINED ON
MINIATURE TENSILE SPECIMENS OF 304 STAINLESS STEEL

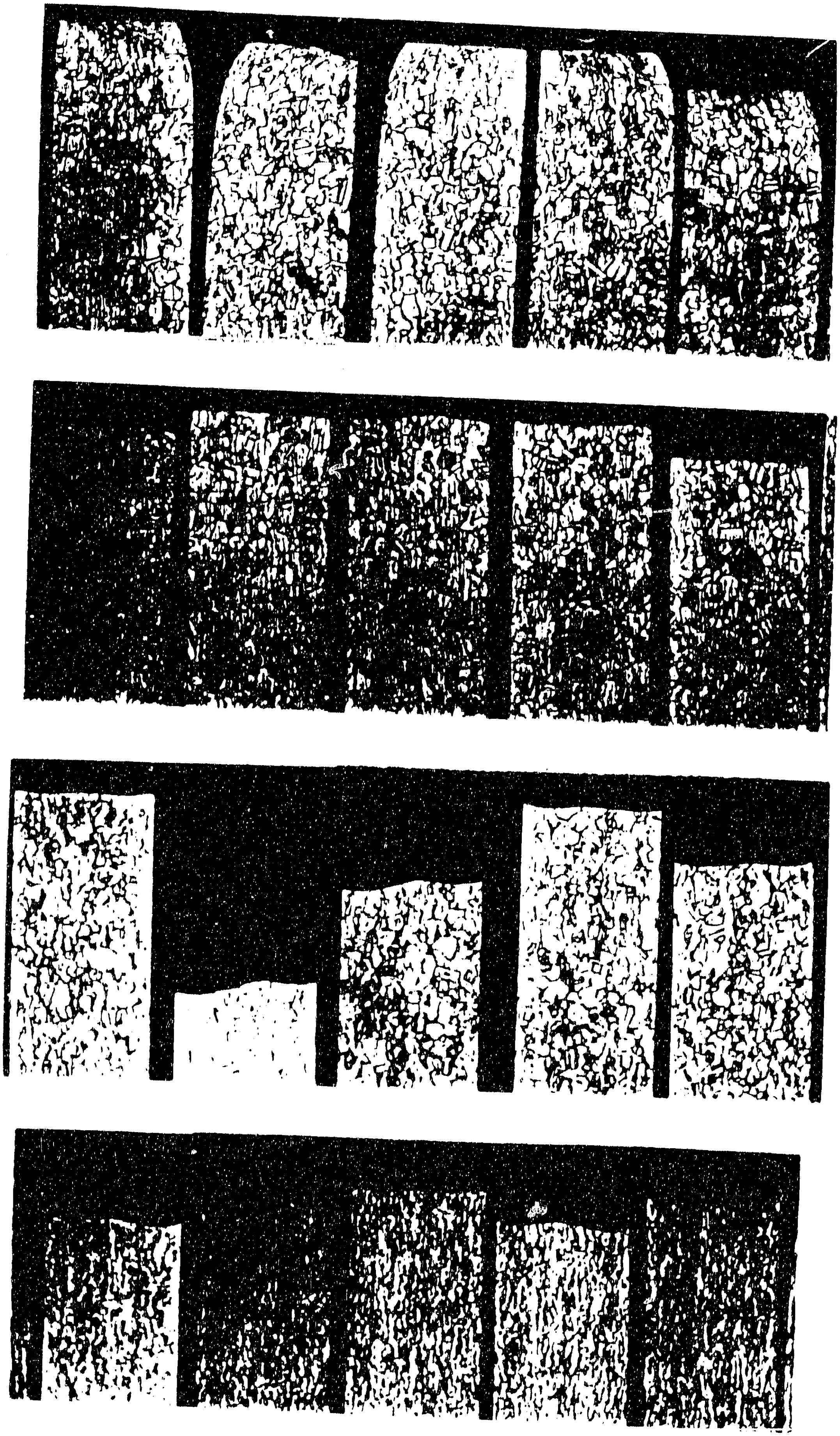
Production process	Yield Strength (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)	Equivalent Cold Work Level (%)
PNL-supplied material (solution annealed 304 stainless steel)					
Punching	44.4 ± 2.4	92.4 ± 0.9	46.6 ± 1.4	49.9 ± 1.4	3
Chemical milling	37.8 ± 0.4	91.3 ± 0.6	66.5 ± 3.3	73.2 ± 2.8	1
EDM	38.1 ± 1.3	90.8 ± 0.3	59.6 ± 1.7	68.0 ± 2.5	1
Previously punched	55.5 ± 2.4	101.5 ± 1.1	35.5 ± 2.9	38.5 ± 3.0	5
Vendor-supplied material (hardened 304 stainless steel)					
Chemical milling	109.0 ± 5.5	134.0 ± 1.5	7.1 ± 1.3	7.1 ± 1.3	25

1

SHEET-TYPE



tolerances ?



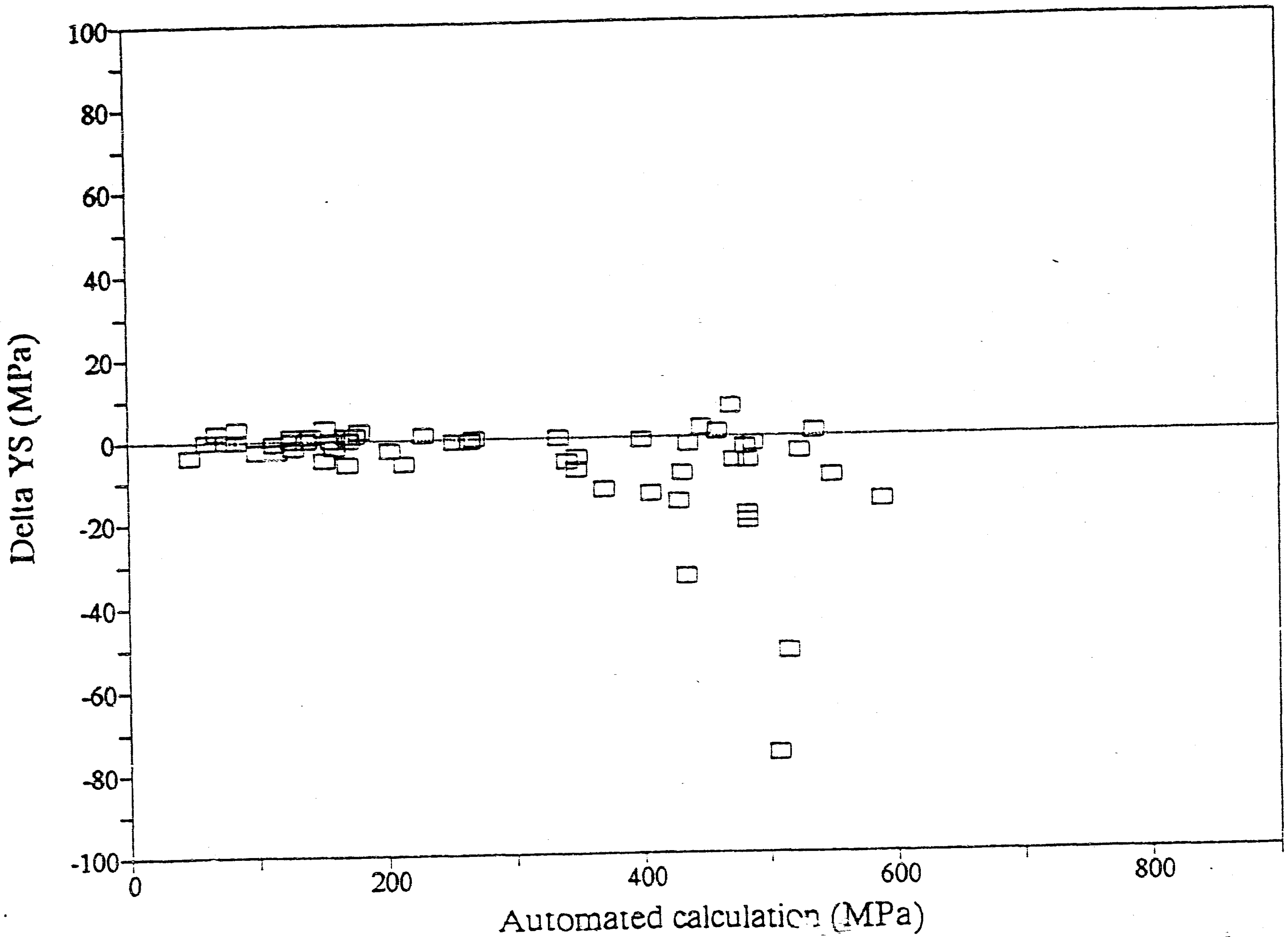
(a)

(b)

(c)

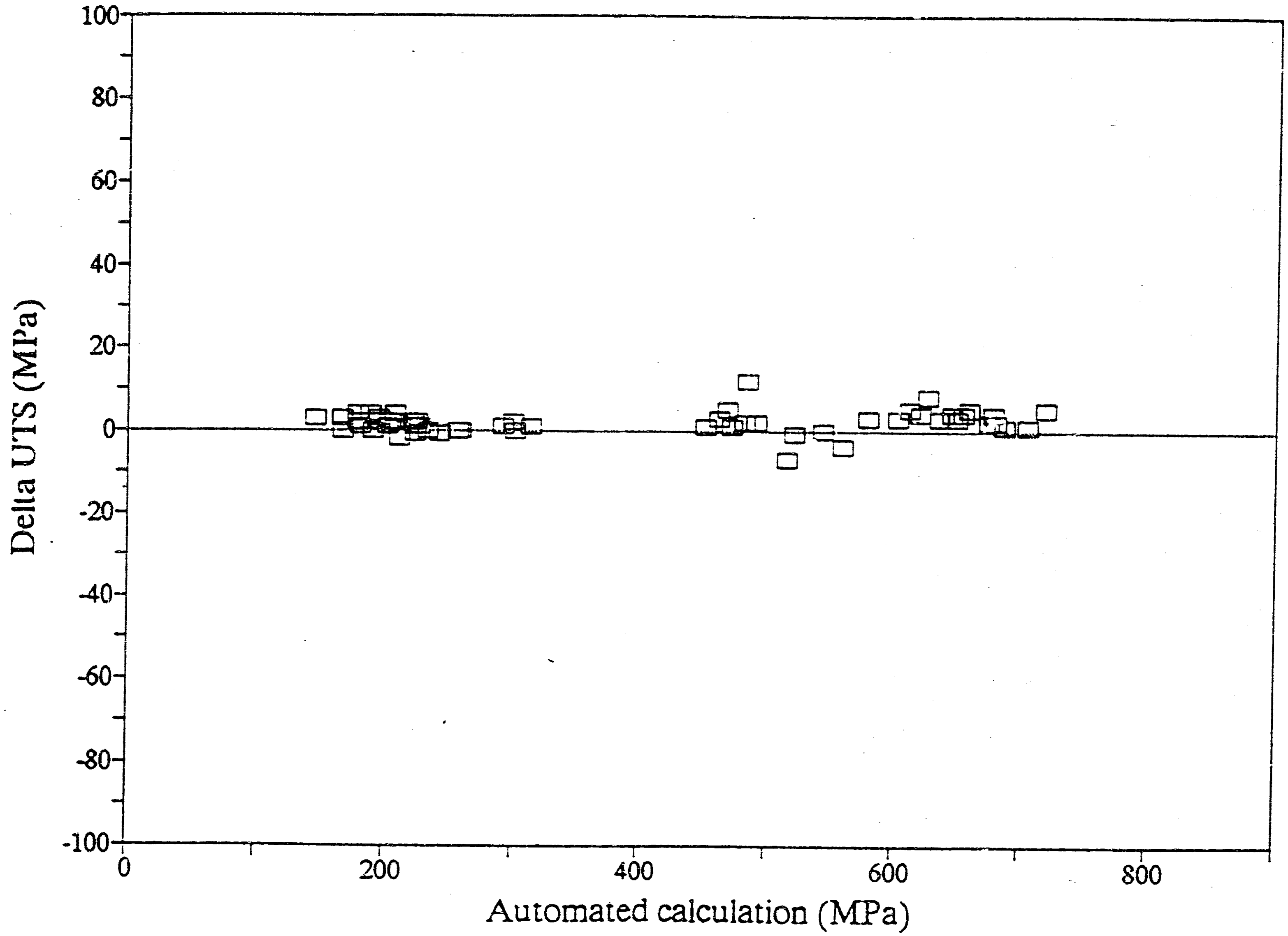
3a

YIELD STRENGTH VARIABILITY

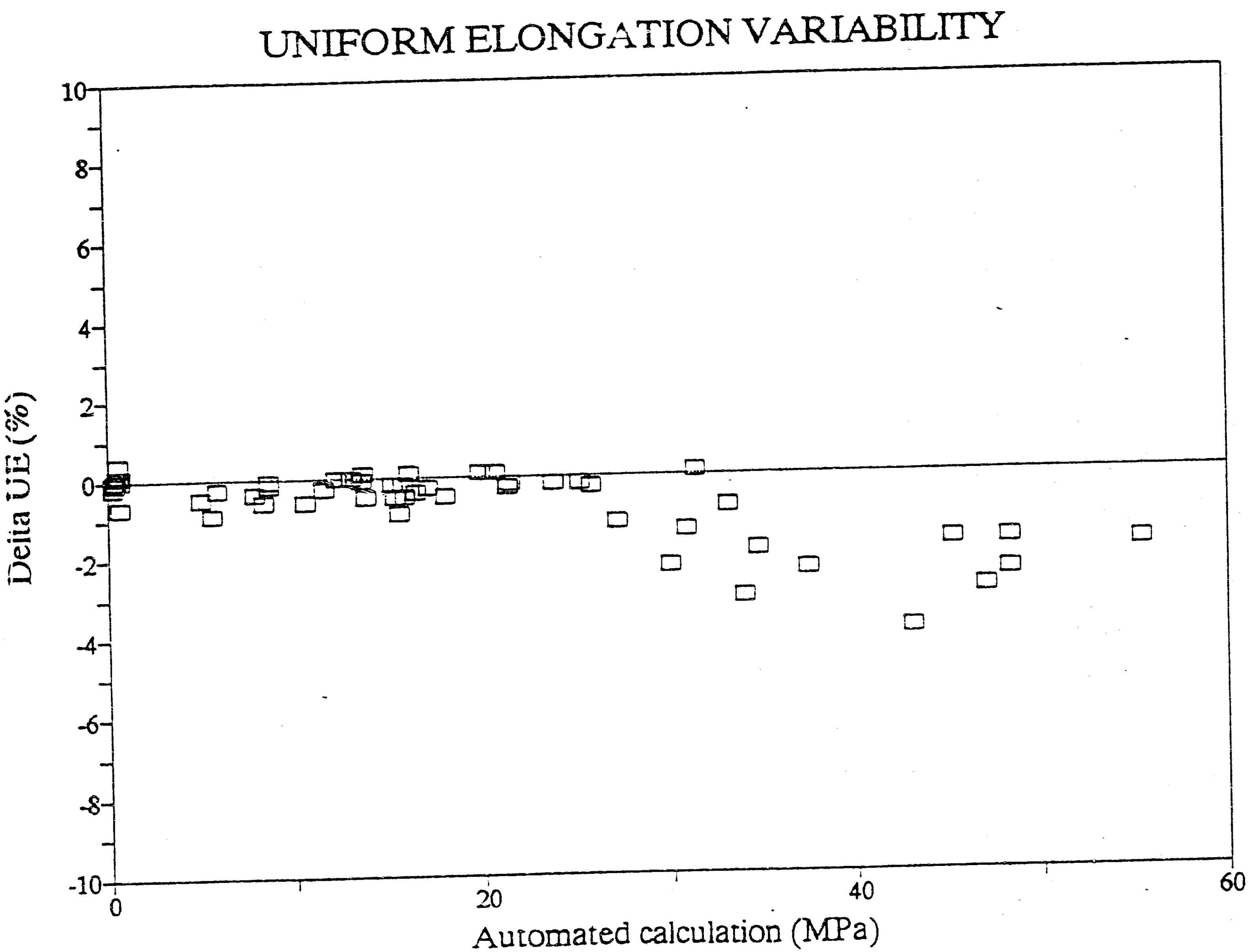


36

ULTIMATE STRENGTH VARIABILITY

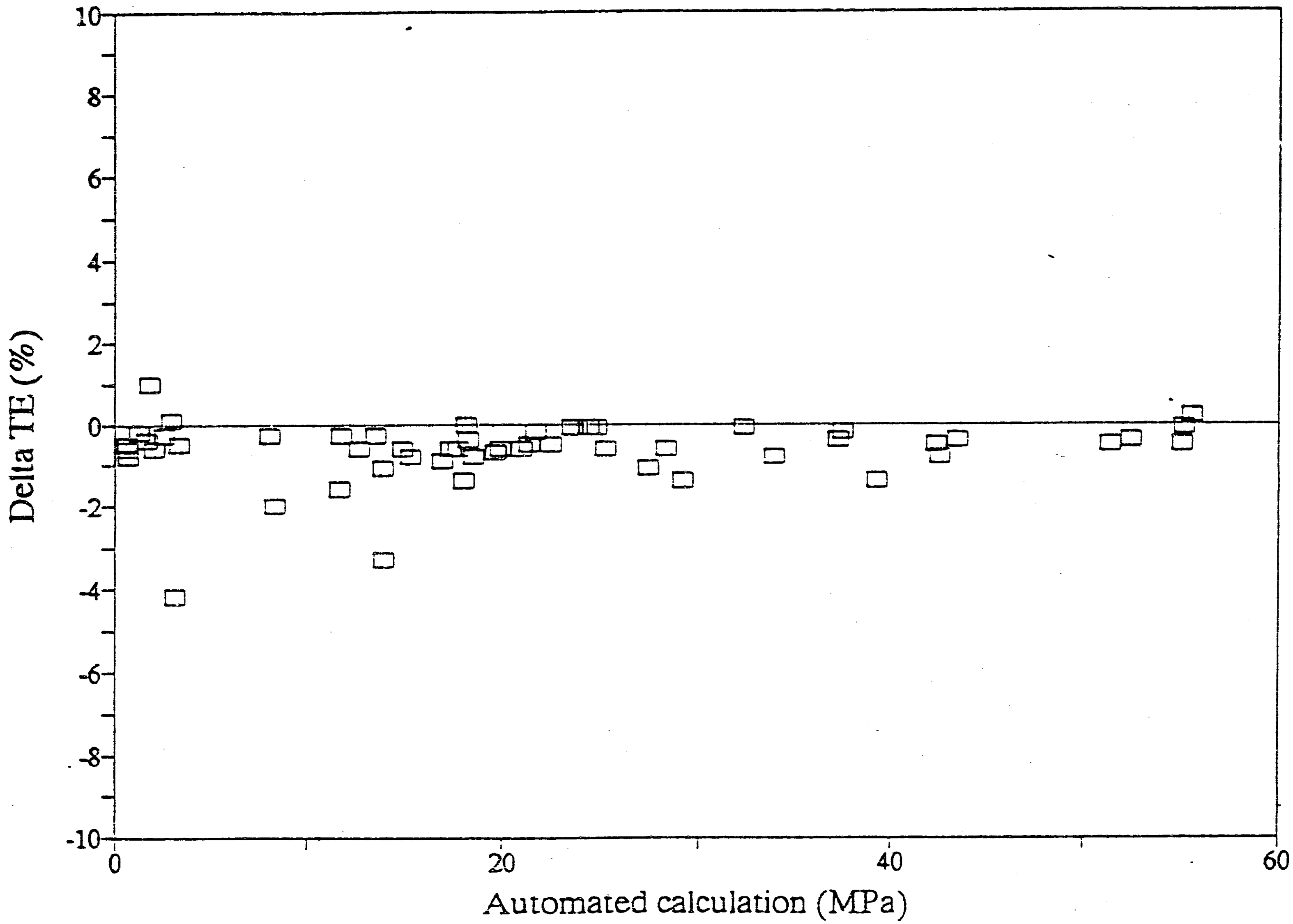


(3c)


UNIFORM ELONGATION VARIABILITY
Delta UE (%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
20
40
60
Automated calculation (MPa)

3d

TOTAL ELONGATION VARIABILITY



The metallography shown in Figures 1 and 4 and the hardness and tensile data given in Tables 1 and 2 demonstrate that punching is likely to alter the structure at the edges of the specimens. Punching could therefore only be considered acceptable if the specimens produced were heat treated following fabrication to remove the deformation remaining at the specimen edges after punching.

It is difficult to assess the effects of cracks that can be produced at the specimen edges; certainly it is impossible to remove them after they are introduced. One example of such cracks, produced in specimens of A212B, is given in Figure 5 (before deburring).[2] While such cracks do not typically lead to errors in the determination of cross sectional area, they are likely to lead to premature fracture of the specimen.

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(a) (b) (c)

Figure [illegible] Miniature tensile specimen of PE16 showing (a) band delineating the size of the sheared zone that resulted from punching, (b) the degree of cupping that lead to the sheared zone. (c) Marz copper specimen showing nonuniformity of curved edges.

Figure 5. Cracks prod

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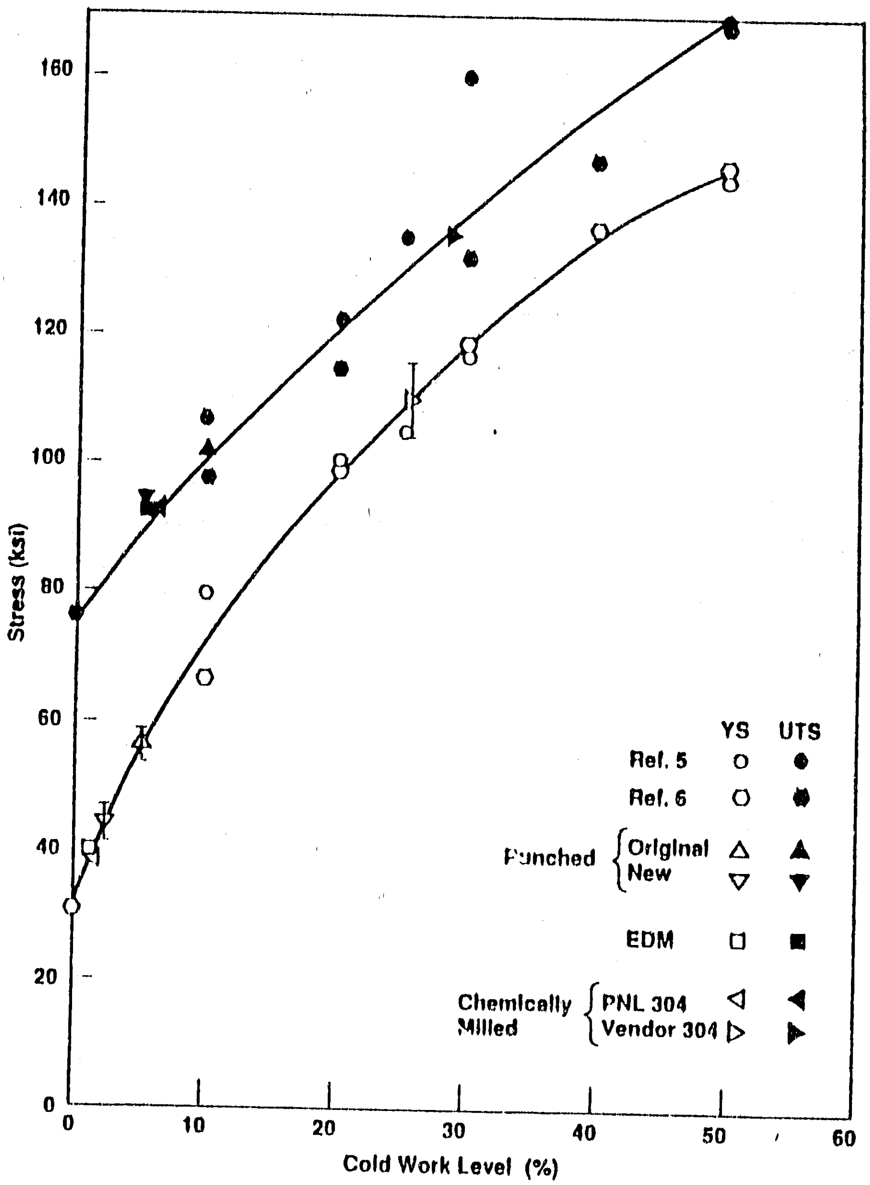
The tensile data generat
nominally in the solutio
specimens suggest that t
value given for the 0% c
of 304 stainless steel.
quality 304 specimens th
the old punched specimen
lent of about 5% cold wo
punched specimens than f
by other materials, part

The final factor to be c
obviously the cheapest i
should be explored with t
It should be possible to
current work if the clear
mens being made, but appe
$500 and would cost about
only small numbers of the
tially available with che
expensive than the EDM te
tensile specimens is EDM.

CONCLUSIONS

The EDM technique was sel
milling would be cheaper
of specimens typically ma



160
140
120
100
80
60
40
20
0
Stress (ksi)
0
10
20
30
40
50
60
Cold Work Level (%)
YS
UTS
Ref. 5
Ref. 6
Punched
Original
New
EDM
Chemically Milled
PNL 304
Vendor 304

31905018.1

END

DATE FILMED

4 / 28 / 92