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CRITERIA OF DUCTILITY IN UNIAXIAL TENSION

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PHYSICAL METALLURGY DIVISION

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Mines Branch Research Report R 75

CRITERIA OF DUCTILITY IN UNIAXIAL TENSION

by

H. H. Bleakney*

ABSTRACT

The merit of reduction-in-area as a criterion of quality in metals is shown to lie in its influence on breaking stress, but the virtue of elongation is not easy to find. In order to assess the value of elongation, either as a measure of quality or as a guide to design, it will be necessary to separate the overall deformation occurring in tension tests from the localized deformation associated with localized reduction in area. The obstacles to a successful solution of this problem have been shown to be more formidable than is generally appreciated, and a new solution to the problem has been suggested. This solution involves a device by which an electric circuit is broken when the particular value of strain is reached that is to be taken as the point of separation between general and localized deformation.

The report presents results from a number of tests on both low-carbon and alloy steels. These results indicate that the selected criterion of separation is accurately identified by the proposed method; that it gives a satisfactory compromise between too much localized deformation on the one hand, and too little general deformation on the other; and that it is simply and practicably applicable to routine tests.

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Direction des mines

Rapport de recherches R 75

CRITÈRES DE DUCTILITÉ EN MATIÈRE DE TENSION UNIAXIALE

par

H. H. Bleakney*

RÉSUMÉ

La valeur de la striction en tant que critère de la qualité des métaux repose, a-t-il été établi, sur l'influence qu'elle a sur l'effort de rupture, mais la valeur de l'allongement n'est pas facile à établir. Afin de déterminer l'importance de l'allongement, soit pour mesurer la qualité, soit pour servir de guide dans le domaine du dessin, il sera nécessaire de dissocier la déformation totale qui se produit lors des essais en tension de la déformation localisée qui est liée à une striction localisée. Les difficultés que présente la solution de ce problème, on l'a vu, sont beaucoup plus grandes qu'on ne le croit ordinairement, et une nouvelle solution a maintenant été proposée. À cette fin, on utilise un appareil qui coupe un circuit électrique lorsque la déformation atteint une certaine valeur, qui est considérée comme ligne de démarcation entre la déformation générale et la déformation localisée.

Le présent rapport donne les résultats de plusieurs essais portant sur des aciers à faible teneur en carbone et des aciers alliés. Les résultats indiquent que le critère choisi est identifié nettement par la méthode proposée de séparation, qu'il offre un compromis satisfaisant entre une trop forte déformation localisée d'une part et une trop faible déformation générale d'autre part, et qu'il se prête facilement à des épreuves courantes.

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INTRODUCTION

In the 1946 Campbell Memorial Lecture, Gensamer(1) pointed out that there are two quite separate and distinct aspects to ductility in metals. One is related to cohesive strength and the other to the distribution of deformation. In this paper the author proposes to discuss and identify these aspects, to suggest a criterion by which the separate contributions of each may be evaluated in a conventional tension test, and to report the results of an experiment which shows that the suggested criterion may be successfully employed in practice.

THE ASPECTS OF TENSILE DUCTILITY

Because the word ductility has to convey the two different concepts enunciated by Gensamer it communicates a general impression of a quality rather than a precise statement of a property. Widmer and Grant(2) recently introduced a paper on creep-rupture with a comment on the lack of accurate definition in the common use of the term. This general vagueness is clearly exemplified in Webster's New International Dictionary of the English Language, published in 1956, which defines the word ductile as: "Capable of being permanently drawn out or hammered thin; said especially of metals; capable of being moulded or worked". Fortunately, however, although the equivocal message conveyed is an inevitable result of the double duty required of the word ductility, the individual aspects it comprises may be defined with some precision and are even susceptible of useful measurement, at least in conventional tension tests. These tests show that elongation measures the distribution of deformation and they illustrate the relationship between reduction-in-area and cohesive strength.

Reduction-in-Area

The equation of the stress-strain curve explicitly states the functional relationship between reduction-in-area and breaking stress. Gensamer(1) has expressed the equation in the form of $\sigma = \sigma_{1.0}\delta^{n}$, where σ is the true stress, $\sigma_{1.0}$ is the true stress at unit strain, δ is the true strain ($\ln \frac{A_0}{A}$), * and, for any given test, n is a constant indicating the rate of strain-hardening. The dependence of stress on reduction-in-area is at once apparent.

The approximate constancy of n is reliable only in the zone of the maximum load, and the part of the true-stress versus true-strain curve beyond the maximum load usually appears as a straight line. The positive slope of the line shows at a glance how increased reduction-in-area must be accompanied by increased breaking stress. Although the relationship between breaking stress and cohesive strength is not a simple one, it is reasonable to believe that they rise and fall together.

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* A_0 is the original cross-sectional area of the test piece, and A is the area at any given moment during a test.

Elongation

The relationship of elongation to distribution of deformation is less obvious than that of reduction-in-area to cohesive strength. However, the evidence shows that the extent of deformation, before necking begins, depends upon the work-hardening characteristics of the metal, and that the elongation before necking accurately reflects the distribution of deformation. Some especially pertinent examples of this evidence are contained in the following quotations:

Carreker and Hibbard,(3) writing on the deformation of copper, reported that "the uniform elongation that occurs prior to necking increases continuously with decreasing temperature, a logical result of the variation of strain hardening with temperature".

Powell et al,(4) in a discussion of strain hardening in austenitic steel, wrote: "Work by Geil and Carwile established that the uniform elongation, or necking strain of copper, nickel, and two copper-nickel alloys, increased with decreasing temperatures down to -196°C. Now when lower temperatures lead to greater uniform elongation, the increase is explained by the higher, more persistent rate of strain hardening ($\frac{d\tau}{d\epsilon}$) at the lower temperatures.".

Makin and Minter,(5) writing on the mechanical properties of irradiated niobium, noted: "Technologically the most serious irradiation effect is the very large reduction in uniform elongation before fracture (17% to <2%), a consequence of a complete lack of capacity to work harden in irradiated material. Hence deformation once started continues in the same place until fracture occurs.".

Cook and Richards,(6) in a paper on the fundamental aspects of cold-working of metals, observed: "As deformation continues, therefore, the increase in the number of dislocations is accompanied by an increase in the number of those being cancelled, and a state of equilibrium is reached when the number of dislocations disappearing is equal to the number being formed. This explains the fact that there is a limit to the degree to which a metal can be work hardened.".

Bastien et al (7) have shown that the so-called "uniform elongation" may be quite lacking in uniformity, and that the deformation which occurs between the yield point and the beginning of necking frequently occurs as though the metal were being kneaded. The details of the process may be followed by examination of Figures 1 and 2. Evidently the pre-necking deformation is the sum of a great many shifting and recurring local deformations, each in turn work hardening and shifting the deformation to a weaker location. Eventually the work-hardening capacity becomes sufficiently exhausted so that at some section the increased flow strength, resulting from the last increment of deformation, is not sufficient to compensate for the concomitant loss of area. Necking, therefore, begins at this section where subsequent deformation is largely localized. Although the measured elongation is the sum of the small local elongations, it is evident that the percentage elongation is a reflection of the extent to which the deformation is distributed diametrically; and this is a statement of the obvious fact that the uniform elongation is a simple function of the uniform reduction-in-area. It is clear, therefore, that the elongation before necking fairly measures the distribution of deformation.

A CRITERION OF NECKING STRAIN

Since reduction-in-area is the indicator of breaking stress, it is obviously the feature of ductility of paramount importance when tension tests are used to assess the "quality" of metals. This special merit of reduction-in-area has been widely recognized and accepted, a notable example being the exhaustive investigation, by Wells and Mehl,(8) of metallurgical quality in gun tubes. Together with reduction-in-area, however, a requirement for minimum elongation is contained in most quality specifications for mechanical properties of metals, and it would seem to be profitable to obtain a better estimate of the real contribution of elongation than is now available. Reduction-in-area can perform its function of indicating cohesive strength quite independently of whatever the elongation may be: total elongation, however, fails to denote the true distribution of deformation because of the notable contribution of the post-necking strain. To assess the value of the elongation requirement in mechanical property specifications, therefore, it is necessary to isolate the fraction of the total elongation that occurs before necking exerts a significant influence.

Separation of the necking elongation from the total elongation is confronted by two rather imposing difficulties. The first of these is created by the virtual impossibility of detecting the instant when necking begins; and the second exists by virtue of the fact that general elongation continues over the whole gauge length even after necking is well developed. In this section these difficulties will be described and, at least for application to steel, a simple solution will be suggested.

The Difficulties

The impossibility of detecting the beginning of necking has been shown in the work of Bastien et al.(7) They used test specimens carefully machined so that all diameters were uniform along the gauge length. During testing, a straight-edge, fastened to the test specimen parallel to the axis, revealed any variation in diameters where gaps appeared along the line of junction. The authors reported that, in all the cases studied, necking appeared before the maximum load was obtained; and they also reported that the attainment of the maximum load does not necessarily mark the end of unlocalized deformation. The evidence presented in Figure 1 supports one of these contentions but not the other. In the test specimen from which the results shown in Figure 1 were obtained, which had been heat-treated for maximum structural uniformity, the maximum load was reached at an extension of less than 20%. From examination of the figure one could not conclude that necking had started at less than about 27% extension. In this case, therefore, the maximum load had been reached well in advance of whatever strain might be accepted as the beginning of necking. On the other hand, general deformation has obviously continued along the gauge length long after the maximum load was passed, thus confirming the second contention referred to above.

It is clear, therefore, that the difficulties involved in separating the uniform elongation from the elongation belonging exclusively to the necking region are real and formidable. It is impossible, or at least certainly impracticable, to select a unique strain at which necking can be said to begin; and if it were possible to do so it would not solve the problem since it would involve neglect of that significant fraction of the general elongation which takes place after the inception of necking.

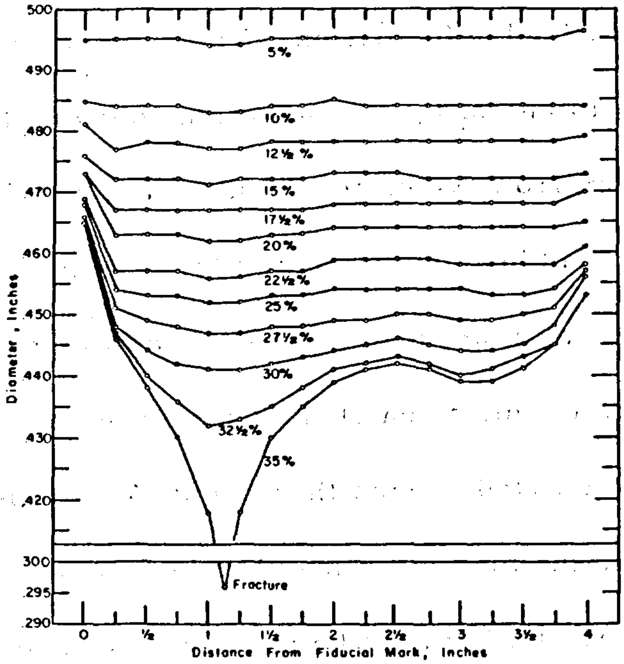

Figure 1. - Distribution of deformation in low-carbon steel measured along one meridian at extensions shown on the curves, as determined in a laboratory of the Mines Branch.

The Suggested Solution

Since any point chosen as the criterion of separation between uniform and localized strain must be a compromise between too much necking and too little uniform extension, the problem reduces to one of selecting a point that is a reasonable compromise, and that can be readily found and reproduced from test to test. The first method that suggests itself in the search for such a point is naturally the conventional one of simply measuring diameters during the course of the test. This method has been used successfully for the construction of true-stress versus true-strain diagrams, but a brief review of Figure 2 shows that it is not readily applicable -- if it is applicable at all -- to the problem of locating the desired criterion.

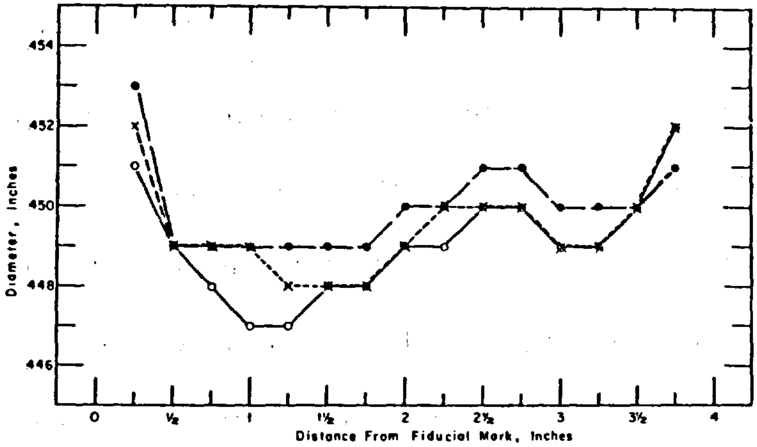

Figure 2. - Distribution of deformation measured along three meridians equally spaced around the circumference. The solid line is the same as that shown in Figure 1 at 27-1/2% extension.

The next most obvious procedure is to try to make use of the maximum load in the selection of the point. Here another difficulty arises. Figure 3 is a load-elongation diagram of a steel very similar to that used in obtaining the data of Figure 1. Figure 4, a magnified view of the part of Figure 3 containing the maximum load, shows that over a range of strain exceeding 5% the maximum load is constant, at least within resolvable limits. This constancy of the maximum load will be recognized by all tensile testing machine operators, who will recall the significant time intervals during which the dial indicator remained stationary at the limit of its travel in the course of each tension test. Hence only two points appear to be usable over this range of strain: the point designated by the strain at which the load first reaches its maximum, and the point designated by the strain at which the load first begins to depart from its maximum.

The gradual rate of approach to the maximum load, illustrated in Figure 3, shows the impracticability of any visual attempt to define the strain at which the load first reaches its maximum. Two other possibilities exist, however. Geil and Carwile$^{(9)}$ have shown that the true strain at the maximum load is equal to the slope of the straight line obtained by plotting the true stress versus true strain curve on logarithmic paper; and Nadai$^{(10)}$ has shown that a line drawn from a point, -1 on the

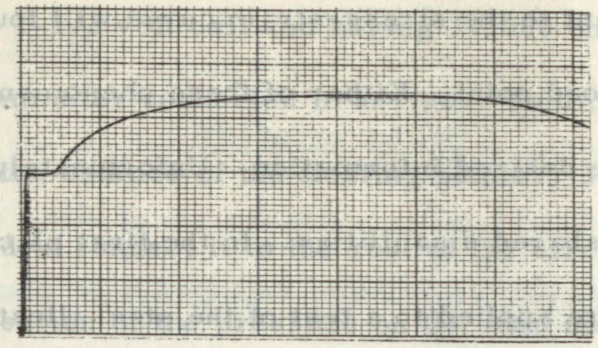

Figure 3. - Autographic load-elongation diagram of a 0.24% carbon steel tension test piece 0.506 in. in diameter and 2 in. in gauge length.

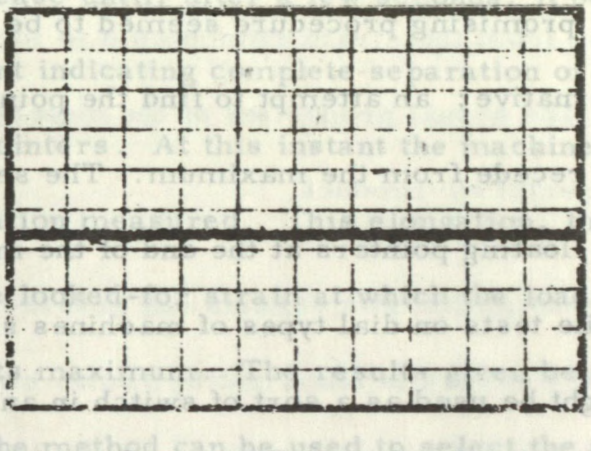

Figure 4. - Same as Figure 3, showing the maximum load between 20 and 25% elongation.

strain axis, tangent to the stress-strain curve will touch the curve at the maximum load point. Either of these phenomena, therefore, should provide the desired information. Unfortunately, both suffer from two equally shared disabilities. In the first place, when these methods were applied to a test of the steel illustrated in Figure 3, values of slightly less than 20% were obtained for the required strain. Figure 1 shows that this extension is only about three-quarters of that which could fairly be classified as pre-necking strain. In the second place, both methods require the laborious and time-consuming procedures involved in true-stress determinations and subsequent plotting of the curves.

A more promising procedure seemed to be suggested by the second alternative: an attempt to find the point at which the load begins to recede from the maximum. The separation of the indicating and floating pointers at the end of the maximum load range during tensile tests on dial types of machines suggested that these pointers might be used as a sort of switch in an electric circuit; and that the instant the circuit was opened would occur at the particular strain being sought for as the necessary compromise. Accordingly, a simple circuit was devised and tested. To obtain maximum conductivity, a load indicator and a floating pointer made from brass strip with silver-plated contacts were incorporated in the dial assembly of a screw-powered Riehle tensile testing machine. Each was made part of an electric circuit powered by a 1-1/2 volt cell and having 33,000 ohms resistance and a microammeter connected in series. To minimize any interference with the balance of the floating pointer, 36-gauge enameled wire was used to connect it to the rest of the circuit. During testing, faint pulsation of the pressure on the load indicator produced vibration of the microammeter needle around an average reading of about 30 microamperes. After the load indicator reached its maximum, with no further perceptible increase, it remained stationary for from ten to seventy seconds, depending on the hardness of the steel and the cross-head speed of the testing machine After such time the average reading of the microammeter needle began to decrease until, after a few seconds, it became stationary at zero current indicating complete separation of the indicating and floating pointers. At this instant the machine was stopped and the elongation measured. This elongation, then, was taken to indicate the looked-for strain at which the load first began to depart from its maximum. The results given below are believed to show that the method can be used to select the value of strain that is the best procurable compromise between too little general elongation and too much necking deformation. The method is also sufficiently practical to be applicable to routine tests, since only a few seconds are required to stop the machine, measure the elongation, and then proceed with the test.

TEST RESULTS

Because the test results reported here show properties of the material tested, a cursory reading might yield the impression that such was the purpose of the work. The author begs a tolerant indulgence if he unnecessarily reasserts that the purpose of these tests was to find out, first if the proposed device would detect the point of strain at which the load indicator just began to recede from its maximum; and second if the point so found was a satisfactory criterion by which to separate the strain attributable to general elongation from the strain attributable to localized reduction in area. The actual properties of the materials under test were an incidental by-product.

The investigation was carried out in three steps: first, a quick preliminary survey (a few sighting shots, as it were); second, an application of the method to as-rolled low-carbon steel; and third, an application of the method to heat-treated alloy steel. A few additional tests will be reported to give an indication of the effect of hardness on the magnitude of strain at the chosen criterion, but this observation must be classed as one of the incidental by-products.

Preliminary Tests

At the very outset of the preliminary tests, two imperfections were noted in the operation of the circuit, both producing excessively wide fluctuations in the microammeter needle. One of these imperfections was unsatisfactory contact between the indicating and floating pointers. By trial-and-error adjustments a sufficiently increased area of contact was obtained to provide acceptable operation. The other imperfection was caused by a slight pulsation in the imposition of the load. Application of a thick grease to the area around the pivot of the floating pointer provided sufficient damping to restrain the pointer from bouncing off the indicator under the action of the pulsating impulses, and reduced the fluctuations of the microammeter needle to tolerable amplitudes.

The device now being operable, three test specimens were prepared from a low-carbon steel bar from storeroom stock in order to check the reproducibility, in terms of strain, of the point where the microammeter needle returns to its zero point. These test specimens were ground to 0.505 ± 0.001 inch diameters over the two-inch gauge length to provide the maximum uniformity of cross sections obtainable within practical limits, in order to minimize the danger that variations in cross sections might affect the reproducibility.

Tension tests on the three specimens indicated a high degree of uniformity in the strain measured at the point where the load began to recede from its maximum. Two of them showed 27% elongation and the third 27.5%. These results were very promising and indicated that the method might prove to be practicable if the established points were found to represent a satisfactory compromise between the two aspects of strain. The load having been removed at the instant when the microammeter registered zero current in each test, and the test specimen thereafter removed from the machine, it only remained to explore the distribution of deformation. To this end the test specimens were painted with mechanic's blue ink, circles were scribed at 1/4-inch intervals along the gauge length, and diameters were measured around the circumference at each interval. Table 1 shows that the results obtained indicate an acceptable division between general reduction and necking reduction-in-area, and that they certainly warrant continued investigation of the method.

Further Tests of Low-Carbon Steel

In addition to the essential objective of acquiring more data, a second purpose in making further tests on low-carbon steel was to examine the extent to which the incipient necking, noted in the preliminary tests, affects the elongation measured at the end of the maximum load. Both purposes were served by conducting tension tests on specimens of varying gauge lengths. Of six tension test specimens machined from a one-inch round bar of 0.24% carbon steel as-rolled, two were provided with two-inch gauge lengths, two others with three-inch gauge lengths, and the last two with four-inch gauge lengths. The object, of course, was to make use of the relationship between gauge length and percentage elongation to obtain the desired information on the incipient necking contribution. In all these tests the load was removed promptly when zero current was shown on the microammeter, and the elongation measured and recorded. Thereafter, however, procedures differed. One each of the three kinds of test specimens was removed from the machine after it was unloaded at the selected maximum load point. In the other three tests the load was reapplied, after measuring the elongation, and the test continued to fracture of the specimen. The pertinent tensile data are shown in Table 2, and they show that the component of elongation attributable to necking strain made no significant contribution to the pre-necking elongation.

The distribution of deformation in these test specimens was investigated by the same method used to obtain the data of Table 1. The results are presented in Tables 3 and 4 and are largely self-explanatory. On the whole they confirm the tentative conclusions drawn from the data presented in Table 1. For the purpose of this discussion, the most significant feature of Table 3 is the difference between the minimum diameter and the average of all diameters measured on each of the test bars outside the incipient neck. In conjunction with the systematically decreasing diameters from both ends of the gauge length to the plane of minimum diameters, the indicated difference between minimum and average in each specimen gives a reasonable assurance that incipient necking has already set in. The diameters at the incipient necks are seen to be less than the average diameters by 0.006, 0.006 and 0.003 inch, respectively, for the specimens with 4-inch, 3-inch and 2-inch gauge lengths.

Although necking has clearly set in at the end of the maximum load, Table 4 shows that significant general deformation occurs thereafter. The average diameters shown at the bottom of the table are from 0.005 to 0.007 inch less than the average diameters of the three unbroken test specimens reported in Table 3. It is evident, therefore, that this additional deformation in excess of the pre-necking strain is of the same order as the amount by which deformation at the incipient neck exceeds the general deformation outside the necked region. This correspondence suggests that the strain at the end of the maximum load range -- the point advocated as the criterion for separation of pre-necking and post-necking strain -- is a satisfactory compromise between too much local deformation and too little general deformation.

Alloy Steel Tests

Six short bars of AISI 4340 steel were heat treated by quenching in oil from 1525°F (830°C) and drawing at 1250°F (675°C). These were machined to tension test specimens, using the same scheme as that adopted for the carbon steel tests: two were provided with 4-inch gauge lengths, two with 3-inch gauge lengths, and the remaining two with 2-inch gauge lengths. These test specimens, as well as all those previously discussed, were machined to 0.505 ± 0.001 inch diameters over the operative length; and they were ground to ensure uniformity of diameters along the gauge lengths. Again the testing procedure was the same as that used for the carbon steel tests.

The results shown in Tables 5 and 6 reveal some similarities to the previously reported figures for the carbon steel. They also reveal some differences. Table 5 shows the remarkable uniformity of elongation at the point where the load begins to recede from the maximum, designated M.L. Elong. in the table. The negligible effect of the incipient neck resembles the results obtained for the carbon steel. A similar general agreement with the carbon steel results is seen in the difference between the average diameters and the diameters at the incipient necks of the unbroken test specimens; and also in the amounts by which the post-necking general deformation exceeds the pre-necking deformation. Some differences are also noted here, however. The differences between the average diameters and the incipient neck diameters for the alloy steel shown in Table 6 -- 0.005, 0.006 and 0.007 inch, respectively, for the three lengths of test specimens -- agree reasonably well with the figures for the carbon steel. Also, the excess of post-necking strain over pre-necking strain for the 2-inch gauge length specimen of alloy steel, 0.008 inch, agrees closely with the 0.007 inch difference shown by the similar specimen of carbon steel. On the other hand, the figures for the other two specimens of alloy steel, 0.000 and 0.002 inch, are noticeably different from the 0.005 and 0.007 inch differences shown by the carbon steel. These variations, however, do not affect the choice of a criterion since they would occur no matter what criterion was chosen. It may be concluded, then, that just as for the carbon steel, so also for the alloy steel: the strain at the point where the load begins to recede from the maximum is the criterion which represents the best compromise in the attempt to identify the pre-necking component of the total elongation.

One other difference between the carbon and the alloy steel specimens was noted. In the tests of the alloy steel all cross sections remained very nearly circular. It is for that reason that Table 6 does not show maximum and minimum diameters

Finally Table 7, as an incidental by-product mentioned earlier, suggests that the effect of increasing hardness is to lower the value of the pre-necking elongation. It is a fairly obvious example of the kind of information to be expected from determinations of pre-necking strain, all such determinations being based on a statistical approach.

SUMMARY AND CONCLUSIONS

Some twenty years ago, the late universally respected H. W. Gillett(11) closed his reply to the discussion of an exhaustive treatise on "The Significance of Ductility in the Tension Test" with the following cogent adjuration: "I still say that when we do not know why we draw a certain provision in a specification as we do, we ought to put in a footnote saying that we do not know". Today there is good reason to believe that reduction-in-area, as a measure of cohesive strength, provides a fair requirement for quality of metals. Elongation, on the other hand, except as it reflects reduction-in-area, seems to offer little if any information of value to either quality control or engineering requirements. The principal purpose of this paper is to emphasize again the continuing desirability of finding out what contribution elongation actually can make as a property of a metal. To this end, the difficulties involved in attempting to separate the necking component from the total elongation have been discussed and a solution suggested. The solution depended upon the discovery of a satisfactory criterion by which to identify a value of strain which would represent an acceptable separation. It was suggested that the strain at which the load just began to recede from its maximum in a tension test would comprise the best combination of practicability and discrimination. A simple device was designed by which to pin-point the proposed strain; and it was used in a series of tension tests which demonstrated that the proposed criterion was acceptably discriminatory and practicably determinable.

Although the details of assembly and operation of the circuit were discussed at some length, this phase of the discussion was mainly to show that a means exists by which the pre-necking elongation can be isolated. The fluctuations of the microammeter needle during the course of a test is an unsatisfactory feature of the device which could undoubtedly be greatly improved. It is quite possible, too, that an entirely different and superior method can be found. It may even be that the straight-edge used by Bastien et al(7) may yield satisfactory results if high precision proves to be unnecessary. The kind of instrument is not important: the important thing -- at least in the author's opinion -- is to begin and continue to accumulate data on the pre-necking elongation of a variety of metals and alloys, in a variety of cold-worked and heat-treated conditions. Thus the true contribution of elongation will be revealed and may be used where it is useful. At the same time -- and perhaps not the lesser of the rewards -- unneeded requirements for elongation may be dropped from specifications when it is found that they serve no useful purpose.

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HHB:(PES) vb

TABLE 1

Distribution of Deformation in Preliminary Work

Inches from Fiducial Mark	Test No. 1 Max (in.)	Test No. 1 Min (in.)	Test No. 2 Max (in.)	Test No. 2 Min (in.)	Test No. 3 Max (in.)	Test No. 3 Min (in.)
1/4	-	-	-	-	-	-
1/2	0.457	0.455	0.456	0.453	0.457	0.452
3/4	0.454	0.451	0.453	0.451	0.457	0.452
1	0.453	0.448	0.451	0.445	0.455	0.452
1-1/4	0.449	0.445	0.452	0.449	0.455	0.448
1-1/2	0.449	0.444	0.450	0.446	0.454	0.449
1-3/4	0.448	0.442	0.450	0.445	0.453	0.447
2	0.450	0.442	0.451	0.445	0.450	0.442
2-1/4	0.451	0.445	0.451	0.446	0.447	0.442
2-1/2	0.454	0.449	0.453	0.449	0.448	0.446
Average	0.449		0.450		0.450	
Minimum	0.442		0.445		0.442	

TABLE 2

Tensile Data on Tests of 0.24% Carbon Steel

Gauge Length, in.	Condition	Max Load, lb	M.L.Elong.[a], %	Total Elong., %
2	Unbroken	14,800	21	
2	Broken	14,800	21.5	37
3	Unbroken	14,750	20	
3	Broken	14,800	21	32.5
4	Unbroken	14,700	21	
4	Broken	14,800	20	31

[a] Designates elongation at the end of the maximum load.

TABLE 3

Distribution of Deformation in Unbroken Specimens of Table 2

Inches from Fiducial Mark	4-in. Gauge Length		3-in. Gauge Length		2-in. Gauge Length	
	Max	Min	Max	Min	Max	Min
1/4	0.465 in.	0.463 in.	0.466 in.	0.465 in.	0.466 in.	0.464 in.
1/2	0.462	0.460	0.464	0.463	0.461	0.459
3/4	0.460	0.458	0.462	0.462	0.458	0.458
1	0.457 (n)	0.456 (n)	0.460 (n)	0.459 (n)	0.458	0.458
1-1/4	0.456 (n)	0.454 (n)	0.460 (n)	0.458 (n)	0.459	0.459
1-1/2	0.456 (n)	0.454 (n)	0.460 (n)	0.459 (n)	0.460	0.459
1-3/4	0.457 (n)	0.456 (n)	0.461 (n)	0.460 (n)	0.460	0.459
2	0.458	0.457	0.462	0.461	0.460	0.460
2-1/4	0.459	0.458	0.463	0.462	0.462	0.462
2-1/2	0.460	0.458	0.464	0.463	0.466	0.466
2-3/4	0.461	0.459	0.465	0.464		
3	0.462	0.460	0.466	0.465		
3-1/4	0.462	0.460	0.466	0.465		
3-1/2	0.463	0.461	0.467	0.465		
3-3/4	0.464	0.463				
4	0.465	0.463				
4-1/4	0.466	0.464				
4-1/2	0.467	0.466				
Average	0.461[a]		0.465[a]		0.461[c]	
Minimum[b]	0.455		0.459		0.458	

[a] Exclusive of diameters, denoted by (n), regarded as belonging to incipient necks.

[b] Average diameter at the minimum cross-section.

[c] Adjustment for incipient neck impracticable.

TABLE 4

Distribution of Deformation in Broken Specimens of Table 2

Inches from Fiducial Mark	4-in. Gauge Length		3-in. Gauge Length		2-in. Gauge Length	
	Max	Min	Max	Min	Max	Min
1/4	0.465 in.	0.463 in.	0.463 in.	0.462 in.	0.462 in.	0.461 in.
1/2	0.462	0.460	0.461	0.460	0.456	0.455
3/4	0.458	0.456	0.457	0.456	0.453	0.453
1	0.451	0.449	0.451	0.450	0.451	0.450
1-1/4	0.440 (n)	0.439 (n)	0.436 (n)	0.436 (n)	0.443 (n)	0.443 (n)
1-1/2	0.407 (n)	0.407 (n)	0.386 (n)	0.386 (n)	0.415 (n)	0.415 (n)
1-3/4	0.320 (n)	0.320 (n)	0.346 (n)	0.346 (n)	0.330 (n)	0.330 (n)
2	0.426 (n)	0.424 (n)	0.422 (n)	0.422 (n)	0.416 (n)	0.416 (n)
2-1/4	0.444 (n)	0.443 (n)	0.445 (n)	0.445 (n)	0.450	0.450
2-1/2	0.447	0.445	0.452	0.451	0.455	0.454
2-3/4	0.446	0.444	0.457	0.456		
3	0.446	0.445	0.459	0.457		
3-1/4	0.449	0.448	0.461	0.460		
3-1/2	0.454	0.452	0.463	0.463		
3-3/4	0.458	0.457				
4	0.461	0.459				
4-1/4	0.463	0.462				
4-1/2	0.465	0.464				
4-3/4	0.467	0.465				
Average[a]	0.456		0.458		0.454	
Minimum[b]	0.320		0.322		0.320	

[a] Excluding diameters, denoted by (n), regarded as belonging to the neck.

[b] At the fractured sections.

TABLE 5

Tensile Data on Tests of Heat-Treated Alloy Steel

Gauge Length, in.	Condition	Max Load, lb	M.L.Elong.[a], %	Total Elong., %
2	Unbroken	23,750	11	
2	Broken	23,450	11	26.5
3	Unbroken	23,450	11	
3	Broken	23,500	11	22
4	Unbroken	23,350	11	
4	Broken	23,450	11	18.2

[a] Designates elongation at the end of the maximum load.

TABLE 6

Distribution of Deformation in Specimens of Table 5

Inches from Fiducial Mark	4-in. Gauge Length		3-in. Gauge Length		2-in. Gauge Length	
	Unbroken	Broken	Unbroken	Broken	Unbroken	Broken
1/4	0.481 in.	0.481 in.	0.476 in.	0.475 in.	0.481 in.	0.475 in.
1/2	0.481	0.480	0.474 (n)	0.446 (n)	0.478	0.462
3/4	0.479	0.478	0.473 (n)	0.355 (n)	0.475 (n)	0.425 (n)
1	0.477	0.464 (n)	0.474 (n)	0.331 (n)	0.472 (n)	0.310 (n)
1-1/4	0.474 (n)	0.420 (n)	0.475 (n)	0.464 (n)	0.474 (n)	0.410 (n)
1-1/2	0.474 (n)	0.298 (n)	0.477	0.471 (n)	0.477	0.456 (n)
1-3/4	0.475 (n)	0.394 (n)	0.478	0.475	0.479	0.467
2	0.476 (n)	0.460 (n)	0.479	0.477	0.482	0.473
2-1/4	0.476 (n)	0.474 (n)	0.480	0.478		0.480
2-1/2	0.477	0.477	0.480	0.478		
2-3/4	0.478	0.478	0.480	0.478		
3	0.478	0.479	0.482	0.477		
3-1/4	0.477	0.479		0.479		
3-1/2	0.478	0.479				
3-3/4	0.479	0.480				
4	0.479	0.481				
4-1/4	0.482	0.482				
4-1/2		0.482				
Average[a]	0.479	0.479	0.479	0.477	0.479	0.471
Minimum	0.474	0.298[b]	0.473	0.294[b]	0.472	0.310[b]

[a] Exclusive of diameters, regarded as belonging to necks or incipient necks, denoted by the letter (n).

[b] At the fractured sections.

TABLE 7

Pre-Necking Elongation of AISI 4345 Steel Quenched in Oil from 1525 °F and Drawn as Shown

Draw Temp., °F	Max Load, lb	Pre-Necking Elong., %
1150	26,550	8.5
1200	25,850	9.5
1250	24,150	12.0

HHB:(PES)vb