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Strain Rate Sensitivity Effect Measured in 316 Steel by the Small Punch Testing Method

Reference

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ABSTRACT

An investigation has been carried out to verify if the strain rate sensitivity effect of 316 steel material can be measured using the small punch test method. It was found that the effect was observed during small punch testing over a displacement rate range of 0.0125–1.25 mm/min, with maximum load increasing as the rate increased, and the strain rate sensitivity exponent m was calculated as 0.018. This result highlights the importance of specifying the strain rate conditions when using the small punch test method.

Keywords

small punch test, strain rate sensitivity, 316 steel

Introduction

Small punch testing (SPT) is a form of biaxial flexure test that has been developed over the past two decades as a small specimen testing technique [1]. The small volume of material required for each test means the technique is of particular use where only a small amount of sample material is available, such as in the development of new materials or where the material may be hazardous (e.g., the nuclear industry). A test standard for the SPT procedure is currently under development [2].

As SPT becomes a more mainstream testing technique, it will be used to test material properties under a wide range of test conditions and for a wider range of applications. In some cases, the test conditions may influence the results. One example of this is the dependence of material strength on the rate of strain application, where strain rate can vary from quasi-static loading through to the very high rates seen in crash or explosive situations.

It is known that the strengths of many materials are dependent on the strain rate, with higher yield and failure stress values being reported as the strain rate increases [3–5]. This is expressed by the following equation [6,7]:

$$\sigma = K.(\dot{\varepsilon})^m \tag{1}$$

where

σ = flow stress;

K = material constant;

$\acute{\varepsilon}$ = strain rate; and

m = strain rate sensitivity exponent.

There are several test methods for determining m [6,7]. One method is to run two continuous tensile tests at different strain rates and compare the levels of stress at the same fixed strain value. Another method is to change the strain rate abruptly during a tensile test and to compare the stress levels before and after the rate change. With the SPT equipment available in this investigation, the easiest test was to run continuous tests at different displacement rates and compare the force levels. Because force is directly proportional to stress and the crosshead displacement is directly proportional to strain rate, m can be calculated from a $\log_{10}$ plot of applied force versus test displacement rate.

The SPT test standard [2] currently recommends that a displacement rate in the range of 0.2–2.0 mm/min should be used for testing specimens. This range may be wide enough to influence the strength results of materials that show strain rate sensitivity. Previous work using SPT to investigate the ductile–brittle transition temperature (DBTT) of ferritic-martensitic steel has included initial studies of the effect of strain rate [8,9]. The results showed conflicting outcomes—the Adams et al. [8] data showed an unexpected shift in the DBTT when tested at two different strain rates, whereas the results from Bruchhausen et al. [9] showed no clear effect on DBTT. From these results, it is not clear whether SPT will be influenced by the strain rate dependency effect. This article summarizes an investigation that focused only on establishing whether the SPT does demonstrate the strain rate effect, with the aim of bringing some clarity to the information currently available.

Method

TEST SPECIMENS

A metallic material was selected for testing that was known to show a strain rate dependency: stainless steel grade 316. At strains of both 5 % and 10 %, this alloy has shown a difference in stress of ~70 MPa over a strain rate range of 0.01–10.00 s^{-1} [5], and the strain rate sensitivity exponent has been calculated as 0.011 [10]. Commercially available stainless steel grade 316 was purchased and cut into disc specimens with a diameter of 8.0 mm and a nominal thickness of 0.5 mm. The surfaces were flat and parallel and finished with grade 1200 silicon carbide paper, as specified in the SPT standard [2].

The hardness of the material was measured using a Vickers micro-indenter.

SPT APPARATUS

In SPT, a disc-shaped specimen is supported at the perimeter while a spherical or hemispherical loading point is pushed into the center at a constant displacement rate. This causes the specimen to deflect in two dimensions, eventually leading to yield and fracture. The applied load and central deflection of the specimen are recorded for the duration of the test.

A schematic diagram of the apparatus used in this investigation is shown in Fig. 1. Concentric support and loading of the specimen was achieved through the use of lower and upper steel dies. The specimen was positioned in a recessed area of the lower die and then held securely in this position by fitting the upper die over it and tightening it to a torque of 10 Nm. The lower die had a hole 4 mm in diameter through its center. The punch head (hemispherical diameter of 2.5 mm) was inserted into the hole of the upper die so that it was positioned at the center of the top surface of the specimen. The punch head was then pushed into the specimen so that the specimen deformed into this hole.

The load was applied by a hydraulic ram to the punch head and a load cell used to record the applied force. A ceramic rod in contact with the center of the lower surface of the specimen transmitted the specimen deflection to a linear variable differential transformer, thus recording specimen deflection.

TESTING REGIME AND ANALYSIS

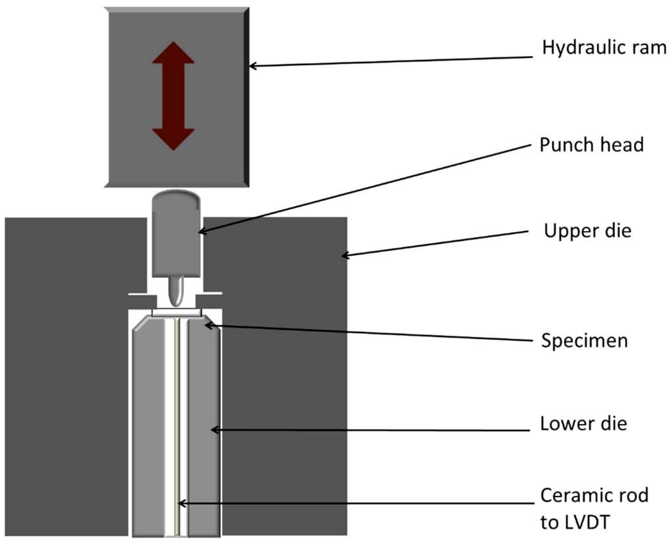
The load was applied at steady crosshead displacement rates of 0.0125, 0.125, and 1.25 mm/minute.

Five specimens were used for each condition, and all tests were carried out in air at room temperature with no lubrication between the punch head and specimen. Both the punch head and the specimen surfaces were checked to ensure they were clean and dry before each test was carried out.

Load was applied until it was obvious that the specimen had failed (taken as the point by which the load had dropped by at least 20 % from the maximum applied load), at which point the test was stopped and a load-deflection graph plotted. At present, SPT graphs cannot be converted directly to true stress–strain graphs so, unlike for standard tensile

FIG. 1

Schematic diagram of the SPT apparatus used in investigation.



tests, it is not straightforward to select a specific strain value for comparison of the corresponding loads. Bruchhausen et al. [9] found that using the maximum load was the most reliable method for calculating the DBTT of grade 91 steel specimens. Therefore, maximum load values, F_{max}, were used to compare the effect of strain rates in this work.

All the load-deflection results were plotted for each displacement rate, and parabola curves were fitted to the graphs in order to smooth the data so that F_{max} could be calculated. The results were averaged for each displacement rate, and the averaged load-deflection graphs were compared. Standard deviation values were calculated to show the variation in F_{max} within each displacement rate batch.

Results

The average hardness value of the steel was measured to be 261 +/− 19.

Plots of load-deflection at crosshead displacement rates of 0.0125, 0.125, and 1.25 mm/min are shown in **Figs. 2–4**. In each case, the plots show the typical response of a ductile material tested using the SPT method, with there being three main stages to the curves: an initial steep gradient, followed by a more gradual curve as the specimen deformed

FIG. 2

Load-deflection plots at displacement rate of 1.25 mm/minute.

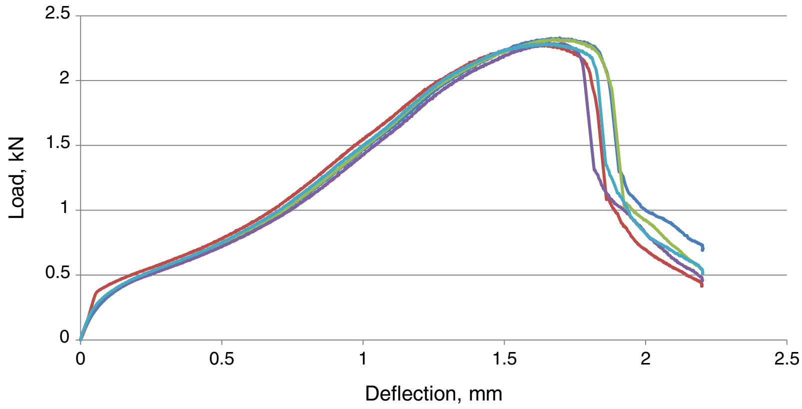


FIG. 3

Load-deflection plots at displacement rate of 0.125 mm/min.

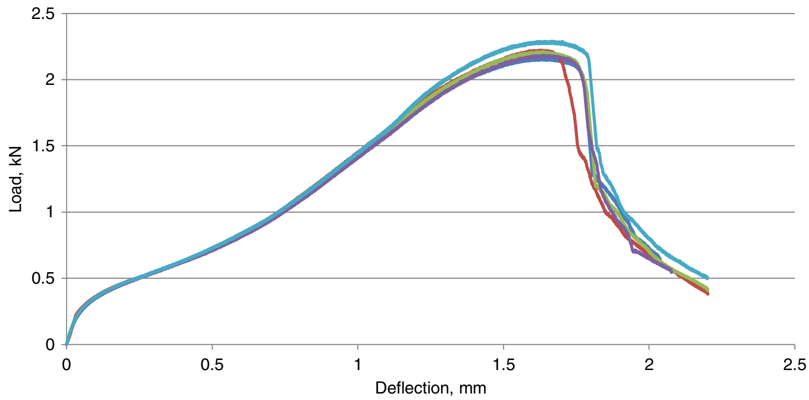
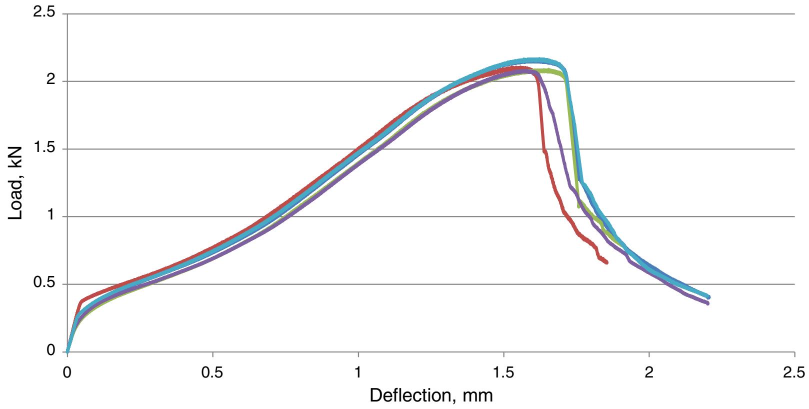


FIG. 4

Load-deflection plots at displacement rate of 0.0125 mm/min.



around the punch head, and finally failure as the punch head broke through the specimen. There is good agreement between the curves within each displacement rate condition.

The averaged load-deflection curve at each displacement rate is compared in **Fig. 5**. This shows that as the rate increased, the maximum load to cause failure also increased. During the initial stage of the test, the curves followed a similar pattern, but the extent of the deviation between the different displacement rate curves became evident as the test progressed. The values for average F_{max} are given in **Table 1**.

In order to calculate m using Eq 1, it must be shown that the force is directly proportional to stress and the crosshead displacement is directly proportional to strain rate.

FIG. 5

Comparison of averaged load-deflection plots for three different crosshead displacement rates (at 1.25, 0.125, and 0.0125 mm/min), with error bars included based on standard deviation analysis.

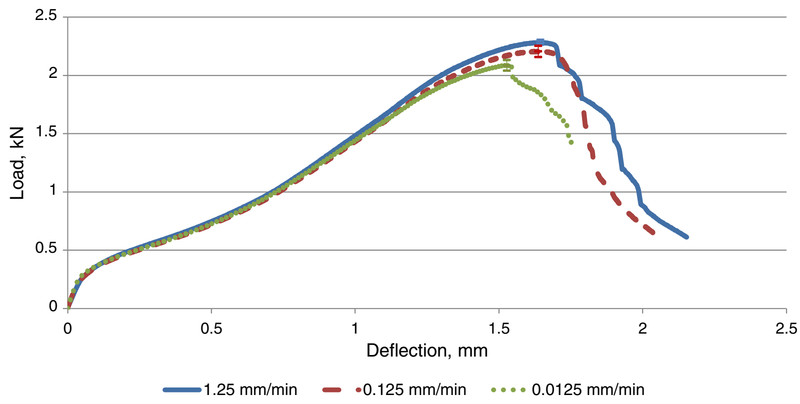


TABLE 1

Average F_{max} values for each displacement rate.

Crosshead Displacement Rate, mm/min	Average F_{max}, kN	Standard Deviation
1.25	2.282	0.021
0.125	2.205	0.048
0.0125	2.085	0.045

This can be done by considering the material velocity and stress at the point of contact between the punch head and the specimen, which are shown as follows:

$$v^* = kv \tag{2}$$

$$d\varepsilon = dl/l \tag{3}$$

$$\dot{\varepsilon} = d\varepsilon/dt = (1/l).(dl/dt) = v^*/l = kv/l \tag{4}$$

$$\log(\dot{\varepsilon}) = \log(kv/l) = \log(k/l) + \log(v) \tag{5}$$

$$\text{Because } \log(k/l) \text{is a constant, } d(\log(\dot{\varepsilon})) = d(\log(v)) \tag{6}$$

$$\sigma^* = F/A \tag{7}$$

$$\log(\sigma^*) = \log(F/A) = \log(1/A) + \log(F) \tag{8}$$

$$\text{Because } \log(1/A) \text{is a constant, } d(\log(\sigma^*)) = d(\log(F)) \tag{9}$$

$$\begin{aligned}\text{Therefore, } m &= d(\log(\sigma^*))/d(\log(\dot{\varepsilon})) = d(\log(F))/d(\log(v)) \\ &= \text{gradient of the graph of log } (F) \text{ versus log (displacement rate)}\end{aligned} \tag{10}$$

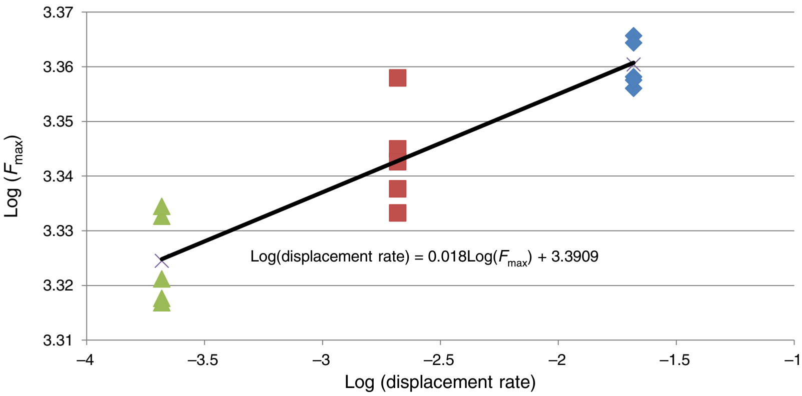
where:

v^* = velocity of material at point of contact between punch head and specimen;
k = constant;
v = velocity of load application;
ε = strain in material;
l = material length;
$\acute{\varepsilon}$ = strain rate;
t = time;
σ^* = stress in material at point of contact between punch head and specimen;
F = applied load; and
A = area of specimen that deforms.

A $\log_{10}$ plot of F_{max} versus displacement rate is shown in Fig. 6. Log_{10} of the average F_{max} values were calculated and also plotted, with the best fit line showing a linear trend

FIG. 6

Plot of log (F_{max}) versus log (displacement rate).



of an increase in F_{max} with rate. The strain rate sensitivity exponent, m, was calculated to be 0.018.

Discussion

The hardness value (Hv 261) was of the order for annealed or 1/4 Hard 316 steel. This meant that the specimens would initially have had a low dislocation density and would be expected to show ductile deformation behavior during testing.

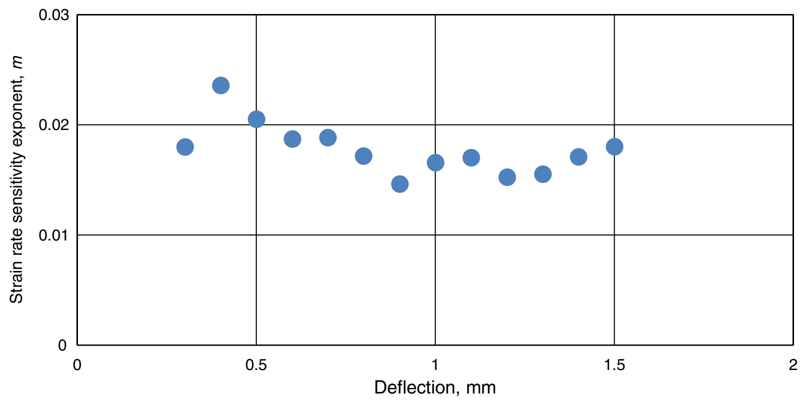
The good agreement between the load-deflection graphs within each rate suggests that the sample material was consistent in microstructure. The shape of all the graphs corresponds to initial elastic behavior, followed by plastic deformation, until rapid localized thinning and fracture of the specimen occurred.

The sample material (316 steel) was selected because it is known to show a strain rate sensitivity effect. Therefore, the increase in failure load with increasing displacement rate that has been observed using the SPT (**Fig. 5**) is in agreement with the trend that has been observed for 316 steel using other test methods. The overlap in the force-deflection behavior at low levels of plastic deformation yield, followed by the divergence as deformation continues, is typical of FCC metallic structures [3]. This suggests that the SPT method did not mechanistically change the nature of the strain rate sensitivity and that this material dependence still plays an important role in this testing method. The strain rate sensitivity exponent of 0.018, calculated from the gradient of the log plot of F_{max} versus displacement rate (**Fig. 6**), compares reasonably well to the value of 0.011 calculated from a jump tension test [10].

It is acknowledged that the F_{max} values used to compare the load-deflection curves in **Fig. 5** and to calculate m in **Fig. 6** are not taken from identical deflection values. This introduces the variable of specimen deformation history into the comparisons. Therefore, m was also calculated using Eq 1 by taking the average of m across the rates at fixed deflection values. A graph of m versus deflection was then plotted and is shown in **Fig. 7**. The value of m shows very good consistency, varying from 0.015 to 0.023 across the deflection range, and provides further evidence that the strain rate sensitivity effect seen in **Fig. 5** is genuine.

FIG. 7

Plot of strain rate sensitivity exponent, m, versus specimen deflection.



This means that the SPT technique is able to detect the more complex dependencies that occur in material behavior because of test conditions, which is encouraging in establishing SPT as a mainstream test technique. It does also highlight the importance of stating test conditions such as strain rate when comparing test data because the technique is not strain rate insensitive.

Conclusion

The SPT method was used to test 316 steel specimens at three different displacement rates, and it successfully demonstrated the expected strain rate sensitivity effect. Therefore, the strain rate dependence of test materials must be taken into account when using the SPT, and this should be highlighted in the SPT standard currently under development.

ACKNOWLEDGMENTS

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