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Determination of Tensile Properties at Increased Strain Rates and Various Temperatures

REFERENCE: Schindler, H. J. and Veidt, M., "Determination of Tensile Properties at Increased Strain Rates and Various Temperatures," *Journal of Testing and Evaluation*, JTEVA, Vol. 25, No. 6, Nov. 1997, pp. 571-575.

ABSTRACT: This paper reports on the development and first application of a low-cost dynamic tension testing method which makes testing at strain rates in the range of 100/s to 500/s and various temperatures as simple as an instrumented Charpy test. The kinematical and kinetic analysis of the newly introduced, reusable clamping device allows the determination of the stress-strain curve from the measured force history during the tearing process. The first results show that the new technique is very promising to determine the influence of loading rate and temperature on the mechanical properties of structural materials, since the measured dynamic tensile properties compare well in absolute value as well as accuracy and reproducibility with those obtained using conventional high-speed tension testing facilities.

KEYWORDS: dynamic tensile testing, high strain rate testing, instrumented impact testing, dynamic material properties

To accurately predict or analyze the mechanical behavior of a structure, the stress-strain curve of the material has to be known for the actual strain rate and temperature. The knowledge of the material behavior at increased loading rates is also important since many structural components such as vehicle components in transportation applications, have to guarantee structural integrity not only under ordinary service conditions but also under special dynamic circumstances such as collisions or impact of small or large objects. However, the data reported in the open literature on dynamic material properties are limited to a few of the most widely used structural materials. Determining these properties experimentally is normally very costly, since the experiments require special testing equipment which is available only in a few laboratories [1,2]. Thus, the effect of loading rate and temperature on the mechanical properties of structural materials is often left to assumptions.

The situation is different in toughness testing. Here, testing under increased loading rate and various temperatures is very common. The Charpy V-notch impact test is one of the most widely used test methods to get information on the influence of loading rate and temperature on the toughness characteristics of a material [3]. With an instrumented Charpy pendulum even more sophisti-

cated toughness testing is possible. For example, fracture mechanics properties can be extracted from the measured load histories during the tearing process of a specimen [4,5]. The increased loading rate actually simplifies the testing in these cases, since neither a special displacement measuring device nor a temperature controlled environment is required.

These considerations have led to the development of a simple, reusable clamping device which allows for the cost-effective determination of the characteristic quantities of a dynamic tension test at different strain rates and various temperatures. The new test method was presented for the first time in Ref 6 and will be discussed in greater detail in the following sections.

Clamping Device

The new clamping device is shown in Fig. 1. It consists of two arms (A) which rest on the supports of the Charpy pendulum at one end and are connected to the tensile specimen (B) at the other. The second ends of the arms are forked in order to pull the specimen symmetrically (compare Figs. 2b and 3). The connection between the fork and the tensile specimen is realized by the cylindrical shoulders (C) that are connected to the threaded ends of the specimen and that are meant to glide along the outside surfaces of the forked ends of the arms during the tearing process in such a way that essentially only a tensile force is transmitted. The two arms are in contact with a central pivot (D) which forms a hinge-like connection allowing for a rotational degree of freedom between them.

FIG. 1—Reusable clamping device for low-cost dynamic tension testing, exploded view.

Manuscript received 12/11/96; accepted for publication 4/14/97.

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FIG. 2—Reusable clamping device for low-cost dynamic tension testing, assembled views: (a) front view, (b) top view.

An important feature of the device is that parts (A) to (D) are fixed to each other by slightly pre-stressing the tensile specimen, forming—so to say—a single rigid body, Figs. 2a, b. This feature is important since it eases handling, enabling tests at different temperatures to be performed by simply pre-cooling or pre-heating the entire clamping device, corresponding to the practice in Charpy V-notch testing [3]. Thus, the major deficiency of similar techniques such as the direct impact tension testing technique, which simply puts a fixture into a Charpy machine, can be removed using the new clamping device.

During the test the instrumented striker of the pendulum hits at the center of the central pivot and causes a movement of the two arms which consists among other things of a relative rotation with respect to the center of the pivot. Hence, the forked ends move apart, the shoulders glide along the cylindrical contact areas, and the specimen is put under tension. Depending on the amount of friction between pivot and arms as well as forks and shoulders, a bending moment will be superimposed. To illustrate the process, three subsequent positions of the clamping device during the tearing process are shown in Fig. 3.

Experiments

Specimens

For the first tests, cylindrical tensile specimens as shown in Fig. 1 were manufactured from a ductile pressure vessel steel of the

FIG. 4—Measured force histories $F(t)$, impact energy $E_0 = 50$ J, temperatures -65°C , room temperature (RT), $+150^\circ\text{C}$.

type 20MnMoNi55. The central cylindrical shaft of the specimens that is expected to undergo plastic deformation is $l_s = 16$ mm long and has a diameter of $d_0 = 2.8$ mm. The diameter of the remaining part of the specimen and its threads is 5 mm.

The same material was also used in a round robin program of the European Structural Integrity Society (ESIS) on high-rate tension testing. The aim of the program was to compare the dynamic material properties which are determined by using "classical" high-rate tension testing facilities like high-speed servohydraulic or pneumatic tension machines and impact facilities. Some of the key results of the program are summarized in Ref 7.

The static material properties were determined to be: ultimate tensile strength, $R_m = 695$ N/mm²; plastic strain at R_m , $\epsilon_m^p = 5\%$; yield strength, $R_e = 530$ N/mm²; and plastic strain at fracture, $\epsilon_f^p = 12.5\%$.

Dynamic Tension Tests

The dynamic experiments were performed on a Wolpert 30/15 K-E pendulum (mass $m_h = 19.7$ kg) using an instrumented DIN striker [8]. An electronic device was used to measure the force as a function of time during the tearing process. The identical measurement system has also been used for instrumented Charpy testing [8,9]. A dynamic force calibration technique was applied which is described in Refs 10 and 11. A Nicolet 440 transient recorder was used for data acquisition.

The material was tested at two impact energies, $E_0 = 150$ J (impact velocity $v_0 = 3.9$ m/s) and $E_0 = 50$ J (impact velocity $v_0 = 2.25$ m/s), and three different temperatures, -65°C , room temperature (RT), and $+150^\circ\text{C}$.

FIG. 3—Three subsequent positions of clamping device during tearing process.

Figure 4 shows three typical $\dot{F}(t)$ signals for the three temperatures tested for an impact energy of $E_0 = 50$ J. The force histories look similar to the signals of an instrumented Charpy test [8]. Since the raw data without any filtering are shown, considerable oscillation is present in the signals. During the first 150 μ s of the test the clamping device is aligned with respect to the center of impact which mainly consists of slight movements of the holder perpendicular to the impact direction. This is the reason why the signals differ from one experiment to the other within this time interval and why the inertia peak, which is normally considered as an important characteristic quantity of an instrumented Charpy test [8,9], is not present in the dynamic tension tests.

The dynamic tension test starts after this alignment phase and lasts about 1.2 ms. After approximately 0.5 ms the force starts to decline again, which correlates with the start of localization of deformation. The fracture process ends for all temperatures with a phase of unstable tearing or shear fracture indicated by the sudden drop in the measured force histories towards the end of the recorded signals.

Figure 5 shows a specimen before and after testing. Measuring the final length and the diameter of the cylindrical part of the broken specimen and assuming volume constancy during plastic deformation, the dynamic plastic strain at fracture, ϵ_{fd}^p and the dynamic plastic strain at the beginning of deformation localization, ϵ_{md}^p can be determined. Within the accuracy of the measurement of these quantities, similar values are determined for these characteristic quantities for all temperatures. The mean values have been determined to be $\epsilon_{md}^p = 10\%$ and $\epsilon_{fd}^p = 21\%$.

Figure 5 shows that the specimen remains almost perfectly straight. This is an indication that only little bending is superimposed on the dynamic tensile load, which implies that friction between pivot and arms as well as at the cylindrical shoulders is small.

Strain Gauge Instrumented Tests

Static and dynamic tests using strain gauge instrumented specimens were performed to quantify the influence of friction. The maximum strain that could be measured in the impact tests was approximately 4%. Strains up to 15% could be measured in the static tests. Figure 6 shows the experimental data of a strain gauge instrumented dynamic test at room temperature at an impact energy of $E_0 = 50$ J.

From the strain gauge signals $\epsilon_t(t)$ on the tension side of the specimen and $\epsilon_c(t)$ on the compression side of the specimen, the normal and bending stresses can be calculated up to the time when the first strain gauge fails. That happened after approximately 0.25 ms at a strain level of approximately 4%. Thus, considerable plastic deformation had taken place before the strain gauge on the tension side of the specimen lost contact with the specimen surface.

FIG. 5—Specimen before and after dynamic tension test.

FIG. 6—Signals from dynamic tension tests using a strain gauge instrumented specimen: force history $F(t)$, tensile strain $\epsilon_t(t)$, compression strain $\epsilon_c(t)$, impact energy $E_0 = 50$ J, room temperature.

From the strain gauge curves the maximum normal stress due to bending can be calculated. Its magnitude is always less than 10% of the normal stress due to tension. It seems that the polished and lubricated surfaces are almost perfectly gliding on one another during the tearing process. The results from the strain gauge instrumented tests indicate that the influence of friction is even reduced for dynamic loading compared with static testing conditions. This beneficial effect can be attributed to the short loading time, which prevents the lubricant from being squeezed out of the contact area and enables it to form a perfect liquid film. A similar effect has been observed in dynamic compressive testing of platelets by means of Kolsky's split Hopkinson bar testing device [12].

Analysis

Similar to instrumented Charpy testing, the deflection of the "specimen," which corresponds in our case to the displacement $s(t)$ of the pivot, is determined from the force history $F(t)$ by integrating Newton's law using the mass of the pendulum m_h and the impact velocity v_0 as input variables [8,9]

$$s(t) = \int_0^t \left\{ v_0 - \int_0^\tau \frac{F(\xi)}{m_h} d\xi \right\} d\tau \quad (1)$$

The arms and the pivot can be considered to be rigid bodies, which permits calculation of the position of every point of these two components from a given displacement function $s(t)$ using simple kinematical relations. Hence, the strain and strain rate in the specimen are known if the kinematical assumption is made that the specimen axis will always lie on the line which connects the two closest points of the forked ends of the arms. The physical interpretation of this assumption is that the specimen tends to remain under pure tension. Thus, the elongation of the specimen is

$$\Delta l(t) = 2 \left[e_0 \sin \alpha(t) + \left\{ \frac{l_s}{2} + r \right\} \cos \alpha(t) - r \right] - l_s \quad (2)$$

where

e_0 = initial eccentricity,

l_s = initial length of specimen as measured between the shoulders,

r = radius of cylindrical part of outside surfaces of forked end of the arms, and

$\alpha(t) = \arctan[s(t)/l_s]$, angle which describes the rotation of the arms (see Fig. 3).

The length l_a is the distance from the center of impact to the anvil. Since an angle α of 4 deg results in a strain level within the specimen which exceeds 25%, the angle α will remain small even for highly ductile metals or plastic materials. Considering only small angles, the engineering strain ϵ is:

$$\epsilon(t) = \frac{2e_0}{l_a} s(t) \quad (3)$$

The stress can be calculated from the quasi-static momentum equilibrium equations of the pivot, the forked arms, and the cylindrical shoulders using the measured force $F(t)$ as input signal. In its most general form, including friction between arms and pivot and at the cylindrical shoulders, seven coupled transcendental equations result which have to be solved numerically. If frictional terms are neglected, the following simple expression for the engineering stress σ can be derived

$$\sigma(t) = \frac{2l_a}{\pi d_0^2 e(t)} F(t) \quad (4)$$

where d_0 is the initial diameter of the cylindrical shaft of the specimen, and the eccentricity $e(t)$ for small angles α is

$$e(t) = e_0 - \left(\frac{l_0}{2} + r\right)\alpha(t) = e_0 - \left(\frac{l_0}{2} + r\right)\frac{s(t)}{l_a} \quad (5)$$

where l_0 is the distance between the two closest points on the cylindrical surfaces of the forked ends of the arms as shown in Fig. 3.

Results

Figure 7 shows the calculated stress-strain curves using Eqs 3 and 4, which correspond to the $F(t)$ signals given in Fig. 4. Again, considerable oscillation is present in the stress-strain curves since no filtering of the raw data is used. Nevertheless, the characteristic quantities like the dynamic ultimate tensile strength R_{md} , the corresponding plastic strain ϵ_{md}^p , the dynamic elastic limit R_{ed} , and the plastic strain at fracture ϵ_{fd}^p can be determined. The results for the

FIG. 7—Stress-strain curves calculated from the measured force histories $F(t)$ shown in Fig. 4.

two impact energies and three temperatures tested are summarized in Table 1.

As expected, the increased strain rate has a significant influence on the dynamic elastic limit R_{ed} . The dynamic elastic limit was arbitrarily chosen to be the peak value of the last oscillation before plastic strains can clearly be identified. Further investigations are necessary to clarify if this point represents the strain rate effect of the material behavior or if it is largely influenced by vibrations and temperature effects.

The strain rate dependence of the ultimate strength R_{md} is less significant. Compared with the static value, a maximal increase of approximately 25% is determined.

In contrast to the tensile stress level, the dynamic plastic strains are almost identical for all temperatures and the two different strain rate levels used in the dynamic tests. The measured plastic strains ϵ_{md}^p and ϵ_{fd}^p are in all cases approximately 80% larger than their static values. The calculated values compare well with those determined from analyzing the broken specimens.

In the ESIS round-robin program the dynamic properties of the material were determined using conventional high-speed tension testing techniques. The measured dynamic ultimate strength values lay between $750 \text{ N/mm}^2 < R_{md} < 810 \text{ N/mm}^2$ for strain rates between $100 \text{ s}^{-1} < \epsilon_p < 500 \text{ s}^{-1}$. The difference of approximately 10% between these values and the R_{md} values given in Table 1 can be explained by the fact that in the round-robin program true stresses were determined and the plastic strain ϵ_{md}^p is approximately 10% as shown in Table 1. Generally, the properties determined using the low-cost dynamic tension testing device are in excellent agreement with the ones reported in the round-robin program.

Conclusions

The results show that the newly developed clamping device is very promising as an inexpensive alternative for the determination of the stress-strain behavior of a material at increased loading rates and different temperatures. Using a standard Charpy pendulum, loading rates in the range of about 100/s to 500/s can be achieved, depending on the chosen impact velocity and the shaft length of the specimen. The tests require only small amounts of testing material; for example, four specimens can be machined from a broken Charpy specimen.

The reproducibility of the experimental results is very good and the measured dynamic properties are in excellent agreement with those of dynamic tension tests using conventional high-speed tension testing techniques. The accuracy of the calculated dynamic material properties seems to be sufficient for most practical applications.

TABLE 1—Characteristic material properties for the ductile pressure vessel steel 20MnMoNi55.

Test Parameters		Characteristic Quantities			
E_0 [J]	T [°C]	R_{ed} [MPa]	R_{md} [MPa]	ϵ_{md}^p [%]	ϵ_{fd}^p [%]
50	-65	925	875	9	19
50	RT	790	715	9	21
50	150	630	630	9	21
150	-65	1225	875	10	22
150	RT	895	725	9	21
150	150	895	655	9	22
static	RT	530	695	5	12.5

Static and dynamic experiments using strain gage instrumented specimens have shown that the influence of friction is very small.

With respect to the dynamic material properties of the ductile pressure vessel steel, the tests have shown that:

- The strain rate has a significant influence on the elastic limit but only a moderate influence on the ultimate strength.
- The temperature has an influence on the characteristic dynamic stress quantities. In the temperature range of -65°C to $+150^{\circ}\text{C}$ the ultimate strength approximately decreases by 30%.
- The dynamic plastic strains are approximately identical for all temperatures and the two strain rate levels used in the dynamic tests. They are approximately 80% larger than the corresponding static values.

Several aspects need further investigation: firstly the interpretation of the load signal in the elastic region and near the elastic limit in order to be able to reproducibly determine the dynamic yield strength, and secondly the effect of adiabatic heating, which is inherently present in rapid testing and affects the plastic behavior. Thus, it is planned to do more tests using different types of materials, simulate the tests using thermomechanical finite element techniques, and improve the data analysis procedure by applying, for example, adequate filtering algorithms.

Acknowledgment

This work was done in the course of research and development sponsored by the Swiss Federal Institute of Materials Testing and Research, EMPA, in Dübendorf, Switzerland, under project #132,163.

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