Instrumented tensile–impact test method for shape memory alloy wires

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ABSTRACT

New instrumented tensile–impact test method is proposed for the characterization of shape memory alloy wires in the strain-rate range from 1 to 10² s⁻¹. The force and the velocity evolution during the impact are registered and, based on these curves, the stress–strain response at impact may be obtained. This method is able to measure strain-rate dependent parameters, such as the direct and reverse stress-induced martensitic transformation stresses or the dissipated energy. Moreover, the accuracy of properties measured with this method, such as the Young’s modulus of the austenitic phase or the permanent strain after load–unload deformation, is higher than those calculated exclusively from the integration of the force–time curves.

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1. Introduction

Shape memory alloys (SMA) are interesting for impact applications due to their unique superelastic behaviour [1,2]. SMA wires embedded in polymer matrix composites have shown to be effective in improving their impact behaviour [3]. The stress-induced martensitic (SIM) transformation is exothermic, whereas the reverse transformation is endothermic. Characteristic stresses and strains of these transformations depend on the temperature, and since the strain rate could change the heat-transfer phenomena, the temperature could change during the loading–unloading path. So, the knowledge of the strain–rate effects on the mechanical properties of superelastic SMA is necessary. Standard tensile-test methods are confined to strain rates below 0.1 s⁻¹ [4] and around 1 s⁻¹ when servo-hydraulic test machines are used [5]. Impact studies have been carried out at strain rates higher than 10³ s⁻¹ [6–9] using Split Hopkinson Pressure Bar (SHPB) technique. Thus, in the intermediate range, from 1 to 10³ s⁻¹, relevant to many applications such as crashworthiness [10], there is a lack of experimental data. The attempts hitherto made to study the SIM transformation at these intermediate strain rates using SHPB have failed because the initial velocity of the striker bar must be set at such a low level that the amplitude of the loading pulse is not large enough to load the specimen beyond its initial transformation strain [8]. However, instrumented tensile–impact method has been applied successfully to polymer characterization in this strain-rate range [11], and in this study, it has been proposed as a useful technique for the impact characterization of the SMA wires in the intermediate range from 1 to 10² s⁻¹. Moreover, the conventional instrumented tensile–impact technique has been modified and the new instrumented method is able to measure with higher accuracy parameters that are strain dependant such as the effective elastic modulus, the dissipated energy or the permanent deformation.

2. Experimental method and materials

In tensile–impact tests, the sample is fixed between the mobile grip and the fixed grip. When a pendulum impactor reaches the lowest point achieving the impact velocity, it hits the mobile grip and the tensile force is transmitted to the sample (Fig. 1). This force is measured at the fixed grip by a piezoelectric sensor.

The most common impact-test instrumentation is based on the registration of the force–time curve and the initial impact velocity [12]. The stress is calculated by dividing the impact force curve by the initial area of the wire. Using Newton’s second law, the stress is calculated by dividing the impact force curve by the initial area of the wire. Using Newton’s second law, the stress is calculated by dividing the impact force curve by the initial area of the wire. Using Newton’s second law, the stress is calculated by dividing the impact force curve by the initial area of the wire. Using Newton’s second law, the stress is calculated by dividing the impact force curve by the initial area of the wire. Using Newton's second law, the displacement δ(t)integrated, Eq. (1), is calculated by two successive integrations of the force data (F(t)):

\[ \delta(t)_{\text{integrated}} = \int_0^t \left( V_0 - \frac{1}{m} \int_0^t F(t) \, dt \right) \, dt \]  (1)

V₀ is the measured initial impact velocity and m is the mass of the impactor system which is accelerated during the deformation, that includes the impactor, the mobile grip and the sample mass. The sample mass (in this case <1 mg) and the mobile grip mass (30 mg for this case) are usually neglected because they are much smaller.
than the mass of the impactor. The strain curve can be obtained by dividing the displacement by the initial length of the sample. In the present work we propose to improve the accuracy by performing additional measurement of the velocity during the impact test with laser-based noncontacting measurement equipment (POLYTEC OFV-505). As illustrated in Fig. 1, the laser beam is focused on the mobile grip. The displacement $\delta(t)_{laser-based}$, Eq. (2), is calculated directly as the integration of the laser-based velocity measurement. In this case it is not necessary to know neither the initial impact velocity, $V_0$, nor the mass of the impactor, $m$:

$$\delta(t)_{laser-based} = \int_0^t V(t) \, dt \quad (2)$$

Tensile–impact tests were carried out in a CEAST pendulum, with an impactor mass of 1.098 kg, by varying the impact velocity from 0.35 to 3.7 m/s. The initial sample length was also varied in order to obtain a strain-rate range from 4.6 to 116 s$^{-1}$. The material tested in this work is a commercially available NiTi SMA, ref. NT09, nominal composition 50.9 at.% Ni, purchased from (AMT) @Medical Technologies. The material was supplied in the form of wire, 0.5 mm in diameter, showing superelastic behaviour at room temperature.

In order to evaluate the accuracy of the instrumented tensile–impact method, the dynamic Young’s modulus of the austenitic phase was measured not only with the instrumented tensile–impact method but also using resonant oscillations. The latter measurements were carried at a frequency, $f$, of around 100 kHz with a strain amplitude $\varepsilon_0 = 10^{-4}$. Longitudinal resonant oscillations of the samples were produced by means of a piezoelectric ultrasonic composite oscillator technique [13]. According to Eq. (3), the parameters of ultrasonic standing waves used yield a strain-rate amplitude of around $6 \times 10^1$ s$^{-1}$:

$$\varepsilon_0 = 2\pi f \varepsilon_0 \quad (3)$$

The values of the effective Young’s modulus were calculated, Eq. (4), from the resonant frequency of the sample, $f_s$, its length, $l_s$, and density, $\rho$:

$$E = 4\mu_s^2 f_s^2 \quad (4)$$

3. Results and discussion

The velocity evolution during the impact test obtained by the integration of the force curve and measured by the laser is shown in Fig. 2; both tests were carried out at an impact velocity of 0.8 m/s and they are representative of all the curves obtained in the studied strain-rate range. During the impact, the velocity decreases as the deformation of the sample becomes greater. The test represented in this figure corresponds to unbroken samples, so at the point of maximum deformation, the velocity is zero. After this moment, the sample begins to recover and the velocity increases in the opposite direction. The last point of each curve corresponds to the time when the contact between the impactor and the mobile grip is lost. This fact implies that the strain rate is not constant during the impact event and will be discussed later. During the impact, dynamic oscillations superimposed to the mean response of the material are observed due to the high contact stiffness between the impactor and the sample.

As can be seen in the curve obtained from the integration of the force data, the fact of neglecting the mass of the mobile grip and the mass of the sample implies that the velocity of the impactor is transmitted instantaneously to the sample when the first contact is produced. However, the velocity curve measured by the laser shows an initial acceleration stage (Fig. 2). The acceleration period ranges between 0.1 and 1.5 ms. Both curves are superimposed after this initial acceleration stage, and they deviate at the end of the impact event. The main consequence of the difference in the velocities at the earliest stage of the impact is that the deformation calculated based on the laser-measured velocity, $\delta(t)_{laser-based}$, Eq. (2), is smaller than that obtained from the integration of the force-time data, $\delta(t)_{integrated}$, Eq. (1). This fact is reflected by the stress–strain curve (Fig. 3) showing smaller strains with laser-based noncontacting measurement. During the loading path, the initial slope is associated to the elastic deformation of the austenitic phase. The plateau corresponds to the SIM transformation, and the second rising zone is related to the elastic deformation of the martensitic phase.
The values reported in Table 1 represent the effective Young's modulus of the austenitic (E_A) and the martensitic (E_M) phases, and correspond not only to elastic, but also to anelastic strains of different origins (residual martensitic transformation, plastic and reversible anelastic strains). While the values of E_A were measured during the loading, the E_M values correspond to the effective modulus of martensite measured during the linear unloading path where mainly the elastic recovery of martensite appears. The modulus of martensite shows much higher discrepancy between the values during loading and unloading than the modulus of austenite (Fig. 3). This fact finds a clear interpretation as due to a much higher anelasticity of martensite wherein strong hysteretic effects between loading and unloading are typical, see e.g. Ref. [14]. The quasi-static values were obtained at 10^-1 s^-1 and were carried out in a uniaxial screw-driven testing machine Instron 4206. The impact values based on the force data and based on the laser measurements were carried out at strain rates between 10^1 and 10^2 s^-1. The results obtained with the piezoelectric ultrasonic composite oscillator technique, strain rate of around 6 × 10^1 s^-1, have been considered as the reference values because the ultrasonic method provides strain rates similar to the ones in the impact loading and the stress amplitude σ_0 = E_0 ε is only around 7 MPa, which is nearly two orders of magnitude below the ones required to induce the martensitic transformation. Therefore, ultrasonic data represent a reference point measured under the same strain rate as in impact tests, but in essentially elastic range. A comparison of the Young’s modulus data in Table 1 shows that the accuracy of E_A obtained by the laser-measured velocity is high, since it is similar to that obtained using the piezoelectric ultrasonic composite oscillator technique and slightly higher to that of the quasi-static tests, whereas the value obtained by the integration of the force data differs considerably. So, the effects of the initial acceleration stage could not be neglected for the impact test analysis. Nevertheless, for impact E_M values obtained by both impact methods and by the quasi-static test are practically the same, which is justified by the fact that during the deformation process of the martensite (zone around the velocity curves pass from zero, Fig. 2), the velocity obtained by the integration of the force data and measured directly by the laser are very close values. Therefore, the fact of neglecting the masses of the mobile grip and the mass of the sample for the conventional instrumented tensile–impact tests technique causes wrong measures of E_A, because the initial acceleration stage is not being taken into account. This may be avoided by performing additional measurements of the deformation velocity during the impact test.

Regarding the strain-rate evolution during the impact tests, it has been said before that the strain rate is not strictly constant along the impact event. This is shown in Fig. 4, where the absolute value of the strain rate is plotted as a function of the strain for the stress–strain curve obtained with laser-based measurement shown in Fig. 3. During the most part of the test, the measured strain rate is within the same order of magnitude than the average strain rate. Only at lower and higher strains, the strain rate differs significantly from the average one. This is inherent to the load–unload tests carried out at high strain rates. For instance, something similar happens for Split Hopkinson Pressure Bar tests, where strain rate cannot be kept strictly constant during the whole test, but it may be considered rather constant [7]. In case of Fig. 4, the average strain rate is 11.9 s^-1 and the standard deviation is 3.1 s^-1.

In case of samples loaded until failure (Fig. 5) in which the strain rate does not reach zero for any strain, the standard deviation of the average strain rate with respect to the measured one is even smaller (2.6 s^-1) than in the load–unload case (3.1 s^-1). Thus, in any case, the strain rate during the instrumented load–unload tensile–impact tests may be considered rather constant.

The reproducibility of the new instrumented tensile–impact test was analysed through the repetition of six tests under the same initial conditions. The two impact tests shown in Fig. 6, which may be considered representative of all the tests carried out, show a good reproducibility. The standard deviation of the plateau stresses is lower than 20 MPa and similar to that observed at low strain rates, while the standard deviation of the permanent strain is 0.22%, higher than obtained at low strain rates.

In order to show the ability of the proposed test method to measure properties that are strain rate dependent, two stress–strain curves loaded until the same stress and carried out at two different strain rates are plotted in Fig. 7. The qualitative differences between the low strain-rate curve (10^-4 s^-1) and impact strain rate (10^1 s^-1) are clearly observed. The transformation stresses are higher at impact than at low strain rates showing a shift in the pseudoelastic curve. The plastic strain after unloading is also higher.

### Table 1

<table>
<thead>
<tr>
<th>Strain rate (s^-1)</th>
<th>E_A (GPa)</th>
<th>E_M (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static</td>
<td>10^-4</td>
<td>60 ± 6</td>
</tr>
<tr>
<td>Based on the force data</td>
<td>10^-1−10^-2</td>
<td>47 ± 10</td>
</tr>
<tr>
<td>Based on the laser measurements</td>
<td>10^-1−10^-2</td>
<td>66 ± 5</td>
</tr>
<tr>
<td>Based on the piezoelectric technique</td>
<td>6 × 10^1</td>
<td>69 ± 1</td>
</tr>
<tr>
<td>Ultrasonic composite oscillator technique</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

**Fig. 4.** Strain-rate evolution during an impact test which corresponds to an unbroken sample that shows direct and reverse SIM transformations.

**Fig. 5.** Strain-rate evolution during an impact test which corresponds to a sample loaded until failure.
at impact while the dissipated energy, as the area enclosed in the load–unload cycle, is slightly lower at impact.

It is well known from the literature which is the evolution of the stress plateau when the strain rate is increased within the low strain-rate range [15]. At quasi-static strain rates, $10^{-4} \text{s}^{-1}$ or lower, the transformation stresses may be constants because the deformation process is isothermal i.e., all the heat generated/absorbed during the direct/reverse martensitic transformation is exchanged with the grips and the surroundings. As the strain rate is increased, the time for exchanging the transformation heat with the grips and the surroundings is less, violating the isothermal condition for the transformation in a sense that a part of the transformation heat remains in a sample and increases its temperature. Therefore, the characteristic stresses of the SIM transformations also increases with the amount of the transformed austenite (transformation strain) since they depend on the temperature, so that when the strain rate is increased only a few orders of magnitude, the stress plateau gets inclined. Further increase of the strain rate by several orders of magnitude, reaching the impact range, has two important consequences. First, the transformation time is drastically reduced, and the overall deformation process can be considered close to adiabatic. Second, the velocity of the transformation front propagation may become higher than the heat exchange between transformed and not transformed parts of the sample. Therefore, despite adiabatic mode of the transformation, the temperature at the transformation front remains constant and therefore the transformation stresses will be rather constant during transformations and higher than at quasi-static strain rates. This situation is impossible in the framework of equilibrium thermodynamics, and reflects the fact that the sample during impact test fails to be in thermal equilibrium. Then, the parallel shift of the pseudoelastic curve at impact strain rates as compared to the quasi-static deformation may be due to this rise in temperature. The study of temperature evolution during the impact is ongoing and will be the subject of a forthcoming studies. The plastic strain after unloading is slightly higher at impact than at low strain rates (Fig. 7). Nevertheless, the high dispersion of results at impact, makes not clear how the plastic strain is influenced by the strain rate. Regarding the dissipated energy per cycle, as the area of the hysteresis loop shown in Fig. 7, this is slightly lower at impact $20.1 \pm 0.9 \text{MJ/m}^2$, than at low strain rates $23 \pm 0.6 \text{MJ/m}^2$. This small reduction in the hysteresis is due to the higher increase in the reverse transformation stresses shown in the impact tests.

4. Conclusions

The main conclusion of the present work is that the new instrumentation of the tensile–impact test method is valid for the characterization of shape memory alloy wires in the intermediate impact strain-rate range (from $1$ to $10^2 \text{s}^{-1}$). The new instrumentation is able to measure parameters that are strain dependant (such as the effective elastic modulus, the dissipated energy or the permanent deformation), with higher accuracy than with the conventional instrumentation.

The use of the laser measure of the velocity during the impact depends on the property itself: whereas for the stress magnitudes (forward and reverse SIM transformations stresses) it is not necessary, for properties dependent on strain (elastic modulus, dissipated energy and plastic deformation) it is essential.

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