Experimental investigation of thermomechanical behaviour of NiTi shape memory alloy under low-velocity impact loading

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Abstract. This paper experimentally investigates the thermomechanical behaviour of NiTi shape memory alloy (SMA) under low-velocity impact loading. The phase transformation temperatures of the NiTi material are measured by means of the Differential Scanning Calorimetry (DSC) method. The impact tests are carried out on a drop hammer impact system, wherein force sensor and infrared camera are used to capture the thermomechanical behaviour of NiTi SMA. Several prime material features of SMA, such as superelastic stress-strain response, stress-induced martensitic phase transformation, residual deformation, heat production and energy dissipation, are observed in the drop hammer test of the superelastic NiTi sheet. Considering the impact test is an approximate adiabatic process, the temperature variation on NiTi sheet is highlighted, due to the latent heat and intrinsic dissipation. This temperature variation will affect the mechanical behaviour of SMA, and therefore bring about complex thermomechanical coupling effect in the low-velocity impact test.

1. Introduction

As a typical smart material, Shape Memory Alloy (SMA) exhibits multiple interesting material features, such as superelastic and shape memory effects. Compared with the classical metallic material with elastic strain of less than 0.5%, the maximum recoverable strain of superelastic SMA can be up to 20% according to the literature [1]. Meanwhile, the relatively low interfacial energy density between martensite variants in SMA can absorb the vibration and impact energies, allows SMA being used as mechanical or acoustical dampers. Due to the salient material features, such as light density, corrosion resistance, biological compatibility, SMA are widely used in a variety of engineering fields, including aerospace, transportation, architecture, robotics, biomedical science, etc.

At the early time, the study focus on presenting the mechanical behaviour of superelastic NiTi shape memory alloy (SMA) wires and found the characteristics of the superelastic wires is well suited for seismic applications, as both the strain-recovering and the energy dissipating features can be easily obtained [2, 3].

This good damping property makes SMA a potential cushioning and sound absorbing material [4-6]. The tests were carried out to study the influence of temperature variation, due to the intrinsic dissipation and latent heat, on the mechanical properties. In addition, the test results performed at
different strain rates show that the temperature variation is more obvious with the increase of the strain rate, and further affect the mechanical properties such as yield stress and residual deformation [7-9].

Experimental or simulation studies of SMA in the field of impact have focused on embedding it in polymers or composites as buffer energy absorbing materials [10-12]. The study of the energy absorption effect and the stress change of the shape memory alloy in the austenite and martensite state have yielded significant results under impact load [13].

However, previous studies were mainly focused on superelastic or martensitic SMA wires. There is a lack of studies for SMA sheets at impact conditions, and a serious lack of investigations for interaction between temperature and force under impact load in particular. This paper aims to investigate the energy absorption, phase transformation, residual deformation and non-instantaneous between temperature and mechanical time characteristics in the course of the low-velocity impact process for SMA sheets. The impact properties of the SMA sheets are investigated in detail at the temperature range over \(A_f\).

2. Testing methodology

2.1. Materials and specimens

The material used in the experiment is superelastic NiTi SMA with austenite phase at room temperature. Phase transformation of SMA can be induced when temperature changes. The phase transformation temperatures of the NiTi SMA were measured by means of the Differential Scanning Calorimetry (DSC) method. As seen in figure 1, the start and finish temperatures of the R-phase transformation, \(R_s\) and \(R_f\), are 11.667 °C and -1.545 °C; those for martensite transformation, \(M_s\) and \(M_f\), are -29.177 and -57.117°C, while for austenite, \(A_s\) and \(A_f\), are 4.031 °C, and 28.188 °C. To achieve the superelasticity at room temperature, the NiTi specimens were heat treated (natural cooling after heating preservation at 500°C for 1 hour) before the impact test. The specimen is a 150mm\(\times\)100mm rectangle sheet, with the thickness of 1mm, as shown in figure 2. All the specimens were polished with SiC test paper to ensure a consistent surface roughness.

![Figure 1. Phase transformation temperatures of SMA measured by DSC method](image-url)
2.2. Experimental setup

The low-velocity impact test on the NiTi sheet was carried out on the INSTRON-CEAST 9340 drop hammer impact system, as shown in figure 3. The specimens and the clamp in the impact test are designed according to the standard ASTM D7136/D7136M –12. A new designed clamp was used to hold down two edges of the specimen so that the specimen vibrates as less as possible during impact as shown in figure 3. During the test, the impact force was recorded by the force sensor on the impactor, while the temperature variation was scanned by a FLIR infrared camera SC7000 with frame rate of 115 fps, as shown in figure 3. All specimens were coated with a matte spray paint to maximize the emissivity. The LED lights were used in the test to avoid thermal noise. Here, four impact energies of 10J, 15J, 20J, and 25J were considered.
2.3. Analysis techniques

The core idea of drop hammer impact machine is to instantaneously release a high quantity of impact energy, which was determined using \( E = mgh \), where \( m \) is the mass of the dropped weight remains constant in the test, \( g \) is gravity, and \( h \) is the distance of the dropped weight falls. At the beginning of the impact test, the drop weight was rose to the designated position under the power of the air pump. Before the test, it must be insured that the pneumatic device worked properly and the cabin door was closed. The impact force was recorded by the force sensor on the impactor, while the entire impact data was collected by the data relay station. After the impact test, the drop weight was rose back to the initial position, and the transfer station began to process the experimental data. Data management and analysis were performed using Data Acquisition System (DAS). During the impact procedure, the raw data of the force collected at the time node will be integrated in the workstation through the following numerical integration formula.

\[
\begin{align*}
    t_{\text{sampling}} &= t_i - t_{i-1} \\
    \varepsilon_i &= \sum_{i=0}^{i-1} \varepsilon_j + t_{\text{sampling}} \left( \frac{v_i + v_{i+1}}{2} \right)
\end{align*}
\]

Where \( \varepsilon_i \) is the displacement at the time node \( i \), \( t_{\text{sampling}} \) is the sampling time of two adjacent nodes \( i \) and \( i-1 \) during the whole experiment, \( v_i \) is the deformation velocity obtained from the integral formula (3) below:

\[
v_i = v_{i-1} - t_{\text{sampling}} \left( \frac{F_i + F_{i+1}}{2} - gM_{\text{total}} \right)
\]

Where \( M_{\text{total}} \) is the total weight of the impact bar and counterweights, \( F_i \) is the impact force at time node \( i \). And calculated energy \( E_i \) in main points during the impact are calculated as the area described under force curve in force vs deformation graph by

\[
E_i = \int F(\varepsilon) d\varepsilon
\]

From these techniques the parameters that were investigated include \( E_a \), the dissipation energy during impact, \( F_{\text{max}} \), the maximum force measured by the load tensor on impact, \( D_{re} \), the residual deformation value during the impact, and \( T \), the duration throughout the experiment. These can help us more easily understand bearing state of the specimens under different impact energies. In the low speed impact process, the punch stiffness is large enough to make the deformation negligible, so the maximum depth of the deformed area on the surface of the specimen is equal to the displacement of the punch.

3. Results and discussion

3.1. Mechanical response of SMA sheets

Compared with the quasi-static loading case, the loading time is extremely short and the applied force is much larger, which will give rise to an evident propagation of the internal stress wave. Generally, an austenitic NiTi sheet can undergo large superelastic deformation and dissipate a part of mechanical energy when subjected to an impact load. In order to test whether the impact protection behavior of the NiTi sheet is affected by the impact energy, four levels of the impact energies were considered in the tests. Fig.4 and Table.1 shows the experimental results of NiTi sheets. Curves in Fig. 4(a) represents the force evolution during the impact.
Figure 4. Impact results of NiTi sheets for different impact energies of 10–25J: (a) impact force-time curves, (b) absorbed energy-time curves, (c) a typical force-displacement curve at energy 25J, (d) force-displacement curve at 10J, 15J, 20J.

Table 1. Significant parameter values for SMA sheets at different impact energies.

| Impact energy (J) | $F_{\text{max}}$ (N) | $T$ (ms) | $E_a$ (J) | $D_{\text{re}}$ (mm) |
|-------------------|------------------------|----------|-----------|---------------------|
| 10                | 5193                   | 6.176    | 0.510     | 0                   |
| 15                | 6622                   | 5.872    | 0.826     | 0                   |
| 20                | 7721                   | 5.900    | 1.187     | 0.324               |
| 25                | 8716                   | 5.83     | 0.968     | 0.258               |

The impact force increases rapidly from the initial zero value and reaches a maximum point at 3ms. After the initial fluctuations due to contact between the impactor and the NiTi sheet, the austenite phase near the impact point changes gradually into the martensite. The maximum impact force $F_{\text{max}}$ has a significant heighten effect as the impact energy increases. Though the total time of impact...
process has changed less obviously. According to Table 1, $F_{max}$ is 5193N when the impact energy is 10J. After raising the height to reach 15J, $F_{max}$ reaches 6622N. Similarly, as the value of impact energy grows, the maximum impact force reaches 7721N and 8716N at 20J and 25J. The impact time is approximately 6ms.

$E_a$ is an important parameter to assess buffering capacity of austenitic NiTi sheets. Figure 4(b) gives the absorbed energy evolution of the NiTi sheets calculated by the numerical integral formula (4). The trend of these energy curves is identical to force-time curves, and the maximum energy value is less slightly than the given impact energy value due to the energy loss. The NiTi sheets have a dissipated energy at the end of the curves. It is noteworthy that the dissipated energy keep roughly constant when the loading energy is increased.

Figure 4(c) and 4(d) illustrates typical force-displacement curves. When the energy is 10J or 15J, the residual displacement value obtained by the integral formula is negative. Since NiTi sheets have no residual deformation, the value of $D_{re}$ is considered as zero value. Most of the deformation is reversible upon unloading, while slight plastic deformation takes place, as shown in Table 1. During the impact process, once the NiTi sheets reach the transformation stress, $M_s$, the austenite phase begins to transform into the martensite phase. At the beginning of curve in figure 4(c), the decreased force is because the austenite phase first transforms into the R-phase from the DSC results [14]. Then the force increases as the R-phase begins to transform to martensite phase. It should be noted that the transformation stress is not a constant at different conditions when taking into account the transformation latent heat [15-17]. In particular, the impact energy at 25J is sufficient to facilitate the parent phase completely transform into martensite. The force commences decreasing when unloading occurs, reaching a lower stress limit value of $A_s$, and the reverse martensite phase transformation occurrence after it reaches $A_f$. The force-displacement curves form a nearly closed hysteresis loop, respectively, indicating that the NiTi sheets are capable of dissipating large amount impact energy and exhibit a large deformation recovery ability.

During an impact loading, the superelastic NiTi sheets undergo large deformation and dissipate a large amount of impact energy. In general, the SMA sheet is elastically deformed under low stress conditions. When the stress exceeds the phase transformation stress, the austenite phase transformation begins to transform to martensite phase. At the same time, residual martensite accumulated and austenite dislocation slip take place. It is expected that the NiTi sheets have strong resistance to impact loading as a result of an effective mechanism for dissipating impact strain energy.

3.2. **Thermal effects of NiTi sheets**

During the impact experiment, stress-induced martensitic phase transformation takes place around the impact position, the consequent latent heat gave rise to a noticeable temperature variation on the NiTi sheet. This temperature variation were captured by the infrared camera. Fig.5 gives thermographic image of the NiTi sheet at different times for the impact energy of 25J.

The impact process is too brief for the infrared camera to trace the completely precise temperature variation. However, the thermographic images still illustrate temperature variation tendency on NiTi sheets.

The temperature rise on the NiTi sheets takes place in a relatively large region at the impact moment, as shown in figure 5(c). But then it shrinks quickly due to the heat transfer. Only small region of SMA sheet increases temperature value from figure 5(c) - (d). As the temperature increases, temperature on the back of NiTi sheets rises faster since the in-plane stress at the lower layer is greater than upper layer. Heat transfer from the lower to upper layers requires time. Thus, a time delay between the maximum temperature and the maximum force is noticed, as shown in figure 5 (c) - (e). Finally, the equilibrium temperature is then gradually reduced with convective heat transfer, as shown in figure 5 (f).
Figure 5. Temperature results during impact of NiTi sheets for 25J energy (a) Temperature in the specimen, (b) ~ (f) Temperature change of the NiTi sheet surface as the impact time changes.

The maximum temperature in the region of the impact point under different impact energies is shown in figure 6(a), and only the temperature change value of the impact process is intercepted.

Figure 6. Temperature results of NiTi sheet for different impact energies (a) temperature–time curves, (b) maximum temperature value - impact energy curve.

The maximum temperature value of different energies is 42.87 °C, 44.66 °C, 45.67 °C, and 46.93 °C according to figure 6 (b). One can observe that there is a strong, almost linear correlation between the impact energy and maximum temperature change. As we can see from figure 6 (a), the heating rate under different impact energies is basically the same, and decreases with a slower rate due
to convective heat transfer. The temperature rise of NiTi sheets is mainly due to the latent heat and intrinsic dissipation. It is noteworthy that the curve fluctuation is mainly due to the punch blocking part of the camera detection field, as shown in figure 6 (a). It confirms a time delay between the highest temperature on the top layer of the NiTi sheet and the largest impact force.

The comparative amount of heat is produced during the impact loading and the stress-induced martensitic transformation process. Moreover, there is a non-instantaneous relationship between temperature and impact process, and a linear relationship between the maximum temperature value and impact energy.

4. Conclusions
This study presents an experimental investigation of the complex thermomechanical behavior of the superelastic NiTi sheet subjected to low-velocity impact loading. The temperature variation due to the latent heat and the dependence of transformation stress on the temperature jointly contribute to the thermomechanical coupling effect in impact test of NiTi sheet. The key experiment findings are summarized as follows:

(1) The NiTi sheets exhibit superelastic properties when undergoing large deformation during impact. At relatively small energy levels (10J and 15J) total shape recovery is observed, while at relatively large energy levels small residual deformations are observed, 0.324mm at 20J and 0.258mm at 25J.

(2) The heat production due to the latent heat and intrinsic dissipation during the impact process leads to a dramatic temperature rise up to 29 degrees Celsius, and further affects the mechanical behaviour of SMA, allowing NiTi sheets exhibit unique thermomechanical coupling effect during low-velocity impact.

(3) The superelastic NiTi sheets are capable of dissipating a large amount of impact energy at room temperature. It produces insignificant changes in dissipation energy of only about 1J at different impact energies.

(4) There is a time delay between the highest temperature on the top layer of the NiTi sheet and the largest impact force.

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