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Stress transmission through Ti-Ni alloy, titanium and stainless steel in impact compression test

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Impact stress transmission of Ti-Ni alloy was evaluated for biomedical stress shielding. Transformation temperatures of the alloy were investigated by means of DSC. An impact compression test was carried out with use of split-Hopkinson pressure-bar technique with cylindrical specimens of Ti-Ni alloy, titanium and stainless steel. As a result, the transmitted pulse through Ti-Ni alloy was considerably depressed as compared with those through titanium and stainless steel. The initial stress reduction was large through Ti-Ni alloy and titanium, but the stress reduction through Ti-Ni alloy was more continuous than titanium. The maximum value in the stress difference between incident and transmitted pulses through Ti-Ni alloy or titanium was higher than that through stainless steel, while the stress reduction in the maximum stress through Ti-Ni alloy was statistically larger than that through titanium or stainless steel. Ti-Ni alloy transmitted less impact stress than titanium or stainless steel, which suggested that the loading stress to adjacent tissues could be decreased with use of Ti-Ni alloy as a component material in an implant system.

1. Introduction

Ti-Ni alloy, consisting of titanium and nickel in a nearly equal atomic ratio, is a promising metallic material in many fields due to its special properties of shape memory effect and super-elasticity. Since it possesses high corrosion resistance [1] as well as good biocompatibility [2], it has been increasingly applied to medical and dental appliances, e.g. super-elastic orthodontic wires [3], shape memory vena cava filters [4], shape memory stents [5], super-elastic guidewires, flexible root canal files [6], shape memory dental implants [7], etc. In addition, other applications of Ti-Ni alloy have been reported, such as dental castings [8, 9], orthopaedic implants [10] and intermaxillary fixation wires [11]. This alloy also possesses high damping capacity [12] deriving from high internal friction between the martensitic twins and/or between the martensitic and parent phases.

On the other hand, the difference in mechanical property between implanted material and tissue is likely to prove detrimental to the tissue at the interface. Such a difference is accentuated in metal implants used in major loading conditions, such as joint prostheses and dental implants. The superior damping capacity and quasi-static stress absorption of Ti-Ni alloy have been reported previously [13, 14]. However, it is known that the mechanical properties of materials vary according to the loading rate. The objective of this study is to investigate the impact stress transmission of Ti-Ni alloy in order to evaluate the possibility of using the alloy as a stress shielding biomaterial.

2. Materials and methods

Cylindrical specimens of Ti-Ni alloy (Ti-50.8Ni in mol %, heat-treated at 773 K for 1.8 ks), titanium (Grade 2) and stainless steel (316L) were used. The size of the specimen for impact compression test was 7.0 mm in diameter and height. The Ti-Ni alloy specimens for differential scanning calorimetry (DSC) were prepared from the same series of specimens.

Thermal behavior of the Ti-Ni alloy was measured by DSC to investigate the transformation temperatures of

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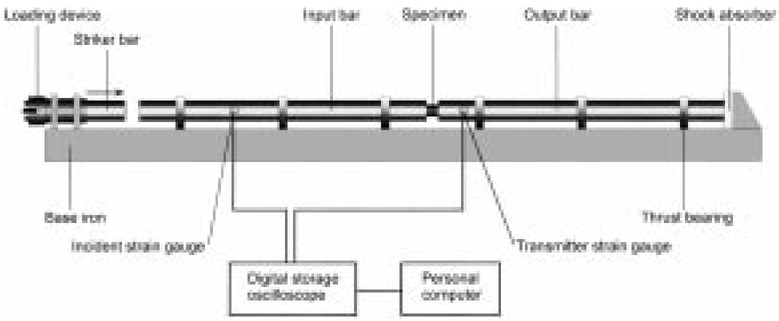

Figure 1 Schematic drawing of the split-Hopkinson pressure-bar apparatus.

the alloy used in the impact compression test. The weight of the specimen was around 40 mg, and alpha alumina powder was used as the reference material. The atmosphere of the measuring chamber was argon gas, and the scanning temperature ranged between 173 K and 373 K. The heating rate was 0.17 K/s. Liquid nitrogen was used for the cooling process.

The impact compression test was carried out by split-Hopkinson pressure-bar technique to investigate the impact stress transmission. A schematic drawing of the apparatus is shown in Fig. 1, where the diameter of the striker bar, the input bar and the output bar was 16 mm, and their lengths were 400, 1500 and 1500 mm respectively. The specimen was held between the input and output bars with lubricant to reduce the frictional constraint and to ensure the contact at the interfaces. The speed of the impact bar was approximately 2 m/s. The stress waves were detected by semiconductor strain gauges bonded directly to the bars and stored in a digital storage oscilloscope for analysis.

Three stress pulses were obtained for each condition. The incident pulse and the reflected pulse were detected by the strain gauge located 490 mm distant from the impact end of the input bar, while the transmitted pulse was detected by the other one at 190 mm from the specimen end of the output bar. The impact test was performed at room temperature, approximately 290 K.

Five specimens were used for each condition of the tests. To compare the impact stress reduction through the three metals, one-way factorial analysis of variance was used for the detection of the differences among metals. Tukey-Kramer test was performed as the *post hoc* test for the detection of the differences between metals. Statistical significance was set at $p < 0.01$.

3. Results and discussion

3.1. Phase transformation

It is known that three kinds of phase transformation can occur in Ti-Ni alloy: $B2 \leftrightarrow R, B2 \leftrightarrow M, R \leftrightarrow M$ [15], where B2, R and M indicate parent, rhombohedral and martensitic phases, respectively. At these transitions, it was reported that internal friction and damping capacity increased [16, 17]. The high damping capacity of Ti-Ni alloy mainly derives from the internal friction between martensitic twins and/or between the phases according to the thermoelastic or the stress-induced martensitic transformation.

Typical thermal behavior of the Ti-Ni alloy, measured by DSC, is shown in Fig. 2. On cooling or heating process, there was only one peak observed, which suggested that the transformation of Ti-Ni alloy specimen used in this study was simple $B2 \leftrightarrow M$ type. The specific transformation temperatures of the Ti-Ni alloy are shown in Table I, where M_s and M_f indicate the martensitic transformation starting and finishing temperatures; A_s and A_f are the reverse transformation starting and finishing temperatures, respectively. Considering the temperature range in which the specimens had been stored, they appeared to consist of both martensitic and parent phases.

3.2. Stress transmission

Typical records of the stress waves through Ti-Ni alloy, titanium and stainless steel are shown in Fig. 3 (a), (b)

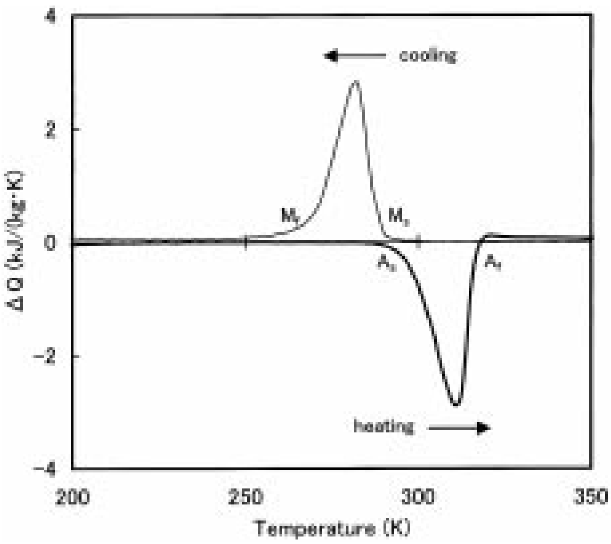

Figure 2 Typical thermal behavior of the Ti-Ni alloy by means of DSC.

T A B L E I Transformation temperatures of the Ti-Ni alloy used in the study

M_s (K)	M_f (K)	A_s (K)	A_f (K)
289.4 ± 1.4	270.2 ± 1.6	297.7 ± 1.8	316.6 ± 0.5

Mean $\pm$ S.D.

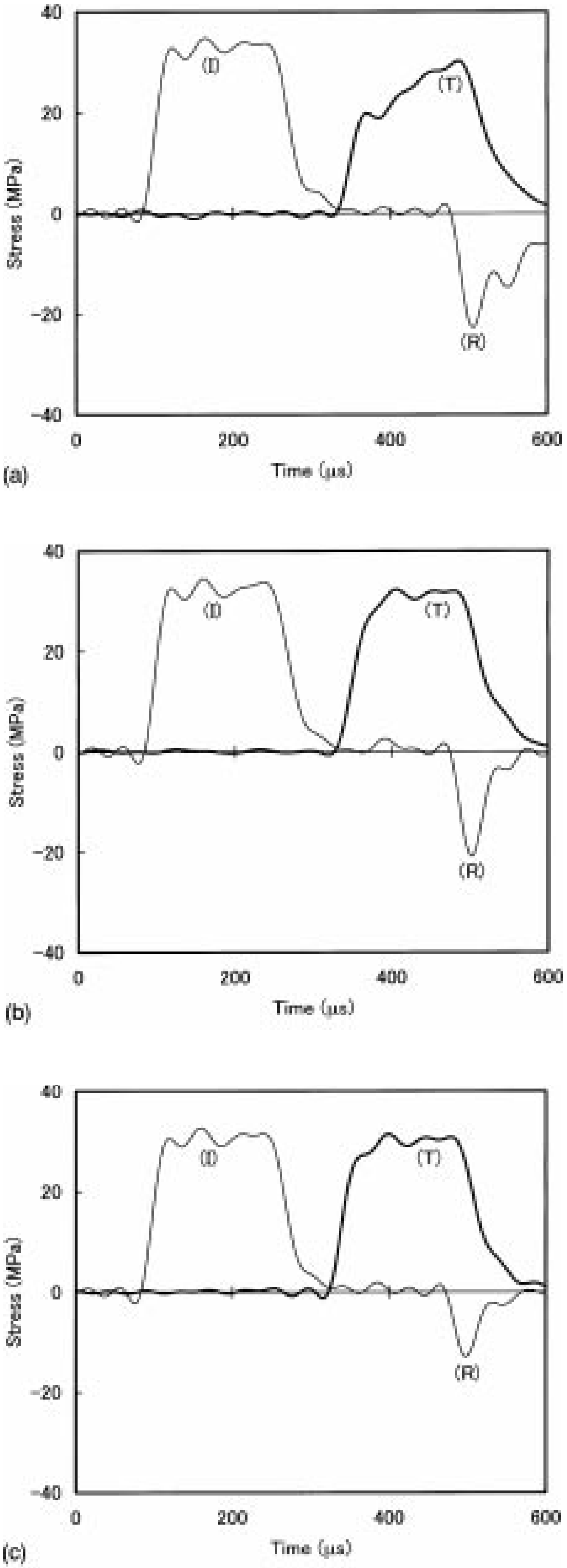

Figure 3 Typical stress waves through (a) Ti-Ni alloy, (b) titanium, and (c) stainless steel. Thin line indicates the stress detected at the input bar, thick line at the output bar. (I) incident pulse; (T) transmitted pulse; (R) reflected pulse.

and (c), respectively. The initial height of the transmitted pulse through Ti-Ni alloy was considerably depressed as compared with the incident pulse, and the stress gradually increased afterwards. The initial stress increase in the transmitted pulses through titanium and stainless steel were slightly lowered from the incident ones. In the last parts of the transmitted pulses, the stress decreased gradually compared with the incident pulses similarly for the three kinds of metals. The forms of the transmitted pulses are thought to reflect the difference in the transmission mode of impact stress through the specimens.

Fig. 4 shows the stress difference between incident and transmitted pulses, $\sigma_I - \sigma_T$ where σ_I and σ_T indicate the stresses of the incident pulse and the transmitted pulse, respectively. This value shows the reduction in impact stress through the specimen. Ti-Ni alloy and titanium exhibited a large stress reduction for the first 20–30 μs. Then, the stress reduction through titanium decreased immediately, while that through Ti-Ni alloy remained at a high level and decreased gradually. The stress reduction through stainless steel was the lowest of the three metals tested, although it also had a small peak at the same point of time.

The stress difference of $\sigma_I - \sigma_T$ is proportional to the strain rate ($\dot{\varepsilon}$) according to the following Equation [18]

$$\dot{\varepsilon} = \frac{2}{\rho_0 c_0 l}(\sigma_I - \sigma_T) \tag{1}$$

where l = initial length of the specimen, ρ_0 = density of the input and output bars, c_0 = longitudinal elastic wave velocity of the input and output bars.

Since the continuous stress difference through Ti-Ni alloy gives a large strain rate of the specimen, this alloy is evaluated to have superior deformability.

Fig. 5 shows the rate of the maximum value in the stress difference between incident and transmitted pulses, shown in Fig. 4, compared with that in the incident pulse; $(\sigma_I - \sigma_T)_{max}/\sigma_{I\,max}$. The value was the highest, 47.4%, for Ti-Ni alloy, while they were 38.7 and 22.6% for titanium and stainless steel. The rate for Ti-Ni alloy or titanium was statistically higher than that for stainless steel ($p < 0.01$).

Fig. 6 shows the rate of the difference between the maximum stresses of incident and transmitted pulses compared with the maximum stress of the incident pulse;

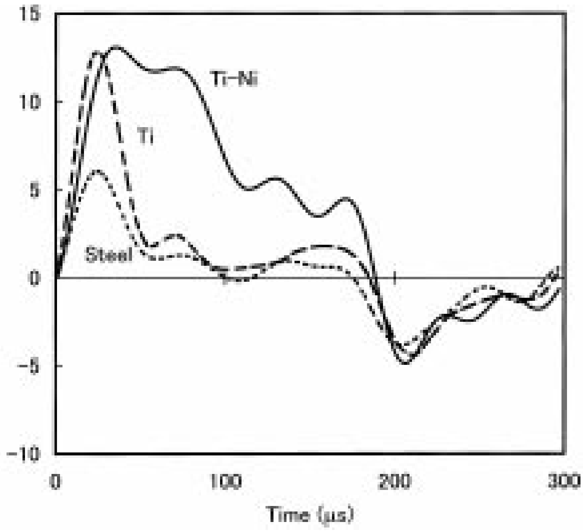

Figure 4 Stress differences between incident and transmitted pulses with respect to time.

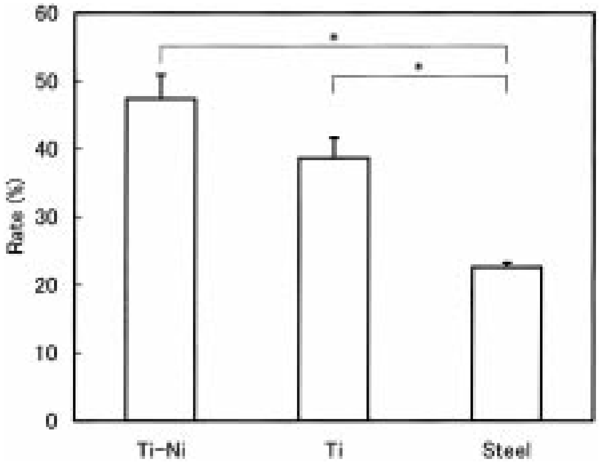

Figure 5 The rate of the maximum value in the stress difference between incident and transmitted pulses. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

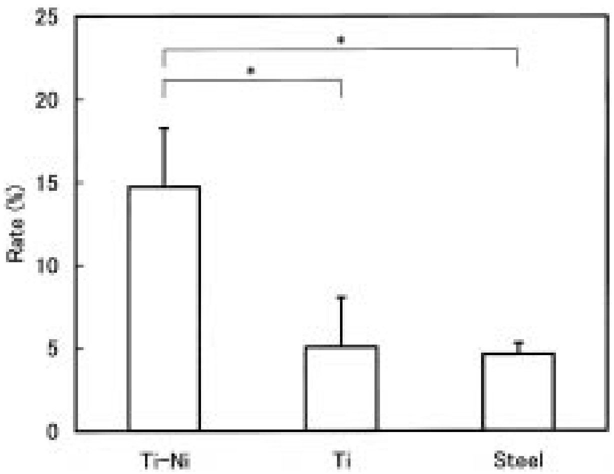

Figure 6 The rate of the difference between the maximum stresses of incident and transmitted pulses. Error bars represent standard deviations. Asterisks indicate statistically significant differences ($p < 0.01$).

$(\sigma_{I\,max} - \sigma_{T\,max})/\sigma_{I\,max}$. The reduction in the maximum stress through Ti-Ni alloy was 14.7% of that of the incident pulse, while those through titanium and stainless steel were 5.1 and 4.6%, respectively. Since the stress reduction in the maximum stress through Ti-Ni alloy was statistically larger than that through titanium or stainless steel, Ti-Ni alloy was evaluated to be effective to decrease the impact stress transmission.

Impact stress transmission through Ti-Ni alloy, titanium and stainless steel was evaluated with use of split-Hopkinson pressure-bar technique with cylindrical specimens. As a result, it was concluded that Ti-Ni alloy transmitted less impact stress than titanium or stainless steel. In addition to the reduction in the maximum stress, the stress reduction through Ti-Ni alloy was more continuous than that through the others showing only a simple peak. It was suggested that the loading stress to adjacent tissues could be decreased with use of Ti-Ni alloy as a component material in an implant system.

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