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MODELING AND SIMULATION OF A SHAPE MEMORY RELEASE DEVICE FOR AEROSPACE APPLICATIONS

Pedro Manuel Calas Lopes PACHECO [1]
Marcelo Amorim SAVI [2]

Abstract

Aerospace applications use pyrotechnic devices with many different functions. Functional shock, safety, overall system cost issues, and availability of new technologies, however, question the continued use of these mechanisms on aerospace applications. Release device is an important example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment or weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices. The Frangibolt is a non-explosive device which comprises a commercially available bolt and a small collar made of shape memory alloy (SMA) that replace conventional explosive bolt systems. This paper presents the modeling and simulation of Frangibolt. This analysis may contribute to improve the Frangibolt design.

Keywords

Shape Memory Alloys, Aerospace Applications, Release Device, Frangibolt.

[1] Departamento de Engenharia Mecânica, CEFET/RJ
20.271.110, Rio de Janeiro, RJ - Brasil

[2] Departamento de Engenharia Mecânica e de Materiais, IME
22.290.270, Rio de Janeiro, RJ - Brasil

Introduction

Aerospace applications use pyrotechnic devices with many different functions. Usually, these devices possess minimum volume/weight, provide instantaneous operation on demand, and require little input energy. Functional shock, safety, overall system cost issues, and availability of new technologies, however, question the continued use of pyrotechnic mechanisms on aerospace applications.

Lucy *et al.*[4] summarizes results of the NASA survey of non-pyrotechnic alternative mechanisms. A comparison of functional shock characteristics of several devices is shown, and potentially related technology developments are highlighted.

Release device is an important example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment or weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices.

The Clementine spacecraft, sent to space in 1994, successfully deployed its solar panels with a non-explosive device, called *Frangibolt*. It provides a simple, safe, and inexpensive way to anchor spacecraft appendages during launch and release them on cue. Frangibolt comprises a commercially available bolt and a small collar made of shape memory alloy (SMA). Frangibolts replace conventional explosive bolt systems possessing inherent risks that range from handling and installation hazards to unintentional activation and fragmentation. Busch *et al.*[2] presents a discussion of Frangibolt design.

SMAs are a metal family with the ability of changing shape depending on their temperature. SMAs undergo thermoelastic martensitic transformations, which may be induced either by temperature or stress. When a SMA specimen is stressed at a constant temperature, inelastic deformation is observed above a critical stress. This inelastic process, however, fully recovers during the subsequent unloading. The stress-strain curve, which is the macroscopic manifestation of the deformation mechanism of the martensite, forms a hysteresis loop. At a lower temperature, some amount of strain remains after complete unloading. This residual strain may be recovered by heating the specimen. The first case, is the pseudoelastic effect, while the last is the shape memory effect (SME) (Tanaka[10], Borden[1]). These effects are inter-related in the sense that, if the hysteresis cycle in the pseudoelastic case is not completed when applied stress is removed, then reversion of residual martensite must be induced upon heating, by employing the SME (Sun & Hwang[9]). In the process of returning to their remembered shape, the alloys can generate a large force which may be useful for actuation (Rogers[5]).

Ni-Ti, Cu-Zn, Cu-Zn-Al, Mg-Cu, Fe-Mn-Si, Cr-Ni are some of the SMAs. The properties of SMAs are very sensitive to composition and processing variables. Ni-Ti (Nitinol) is the most popular SMA as a consequence of a combination of shape memory response with good engineering properties. Strains that elongate up to 8%, can be reversed by heating the alloy, typically with electric current (Tuominen & Biermann[13])

This paper presents the modeling and simulation of release devices using SMAs, specifically, Frangibolt. The authors think that this analysis may contribute to improve Frangibolt design.

Description of the Release Device

Release devices must be load resistant during launch and must be fractured under force generated by the actuator. Frangibolt is a simple release device using SMAs with two main components: A notched bolt element with matched nut and a SMA actuator (Fig. 1).

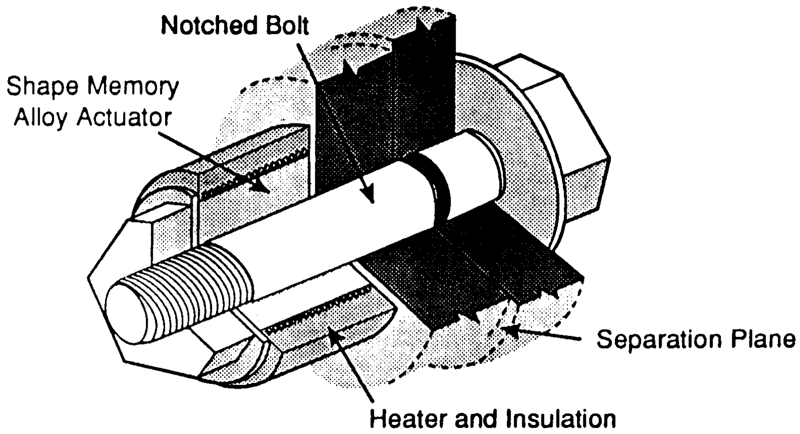


Figure 1: Frangibolt device - Busch *et al.*[2].

The basic idea of the device is to exploit shape memory effect to produce forces that will break the bolt, performing the release. To do it, a pre-compressed SMA cylinder with an integral heater is used as actuator. By heating the actuator, SMA elongates and a force is generated.

Frangibolt has many advantages compared with pyrotechnic devices. It enables non-destructive and repeated testing and greatly reduces the shock of release. The device has two potential limitations: the response time is not immediate and the phase transformation temperature cannot be much higher than 120^0C. Design of Frangibolt must be alert to bolt element (bolt material and notch geometry), actuator element and heater (Busch *et al.*[2]).

A Constitutive Model for SMAs

Microstructural aspects of SMAs have shown that these alloys may present two possible phases: Austenite and Martensite. Martensitic plates may be internally twin-related. Hence, different deformation orientations of crystallographic plates constitute what is known by martensitic variants (Zhang *et al.*[14]).

Phenomenological aspects of SMA behavior are considered by constitutive models, which is formulated to describe the shape memory and pseudoelastic effects. Savi & Braga[7] present an overview of some constitutive models for SMAs. Here, the model with assumed transformation kinetics, proposed by Tanaka and co-workers, is considered (Tanaka[10], Tanaka[11], Sato *et al.*[6]; Tanaka & Nagaki[12]). It is a one-dimensional model which assumes the kinetics of phase transformation establishing a relationship between the martensitic fraction, β, and other internal variables such as temperature, T, and one-dimensional strain, ε. The rate form of constitutive equation is given by,

$$\dot{\sigma} = E\dot{\varepsilon} - \alpha\dot{\beta} - \Xi\dot{T} \qquad (1)$$

where E is the elastic modulus, Ξ is a thermodynamic coefficient and α is a coefficient associated with phase transformation. They are positive constants. The martensitic fraction β can assume a value in the range $-1 \le \beta \le +1$. $\beta = +1$ means that the body is 100% on a martensitic variant M+, which is induced by tensile stresses. $\beta = -1$, by the other side, means that the body is 100% on a martensitic variant M-, which is induced by compressive stresses. $\beta = 0$ is associated with the matrix phase, which may be austenite or twinned martensite, depending on temperature.

Phase transformation is assumed to be determined by the current values of stress and temperature, $\beta = \beta(\sigma, T)$. The transformation from austenite to martensite may be described by an exponential law:

$$\beta = \left\{1 - \exp\left[-a_M (M_s - T) - b_M |\sigma|\right]\right\} sign(\sigma) \quad (2)$$

where $sign(\sigma) = \sigma / |\sigma|$. a_M and b_M are positive constants. M_s is the temperature at which martensitic phase begins to be transformed. This equation holds for,
$\sigma \geq (a_M / b_M)(T - T_M)$.

The reverse transformation is described by another exponential law,

$$\beta = \left\{\beta^M \exp\left[-a_A (T - A_s) + b_A |\sigma|\right]\right\} sign(\sigma) \quad (3)$$

where a_A and b_A are positive constants and β^M represents the volumetric fraction of martensite when the reverse transformation begins to take place. A_s is the temperature at which austenitic phase begins to be transformed. This equation holds for, $\sigma \leq (a_A / b_A)(T - T_A)$.

Modeling of the Release Device

Frangibolt modeling proposed here considers that all components, except SMA actuator and bolt, are rigid. Figure 2 shows device and model schematic diagrams.

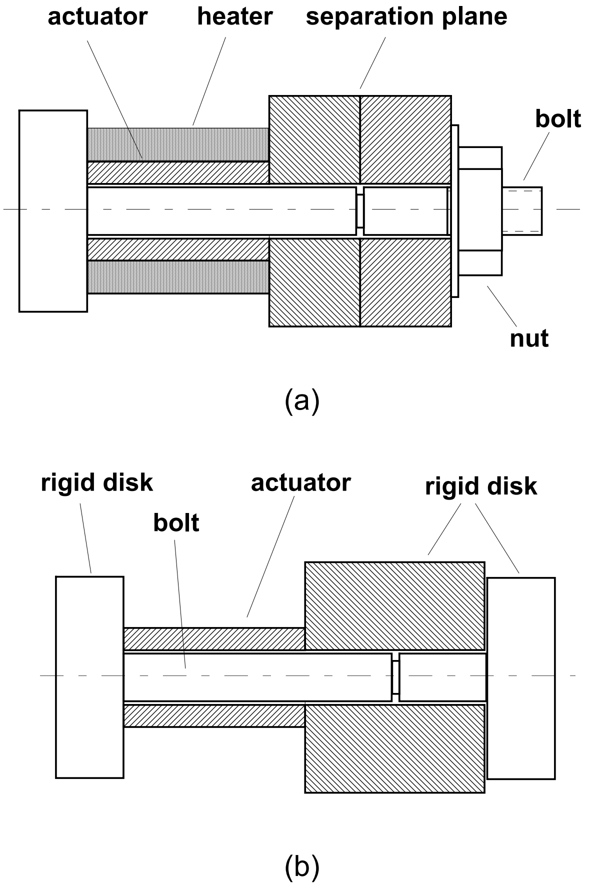


Figure 2: Scheme of Frangibolt release device. (a) Device and (b) model.

By heating the pre-compressed SMA actuator, it elongates causing the bolt deformation. The rate form of displacement on each element is given by:

$$\dot{u}_B = \frac{\dot{P}}{K_B} \tag{4a}$$

$$\dot{u}_S = \dot{\varepsilon}_S L_S = \frac{L_S}{E_S}\left(\dot{\sigma}_S + \alpha\dot{\beta} + \Xi\dot{T}\right) \tag{4b}$$

where P and K_B is the force and stiffness of the bolt, respectively. L_S is the actuator length. For the geometry adopted, finite element simulations of the notched bolt shows that a linear relationship between force and displacement can be assumed without any loss in the elastic region (Busch *et al.*[2]). By compatibility requirements,

$$\dot{u}_B = \dot{u}_S \tag{5}$$

By considering the force P that acts on both elements (compressive on SMA actuator and tensile on bolt), equilibrium establishes that,

$$\sigma_S = -\frac{P}{A_S} \tag{6a}$$

$$\sigma_B = \frac{P}{A_B} \tag{6b}$$

Hence, it is possible to write,

$$\dot{\sigma}_S = -K\left(\alpha\dot{\beta} + \Xi\dot{T}\right) \tag{7}$$

where $K = \dfrac{1}{1 + (K_S / K_B)}$ and $K_S = \dfrac{E_S A_S}{L_S}$ is the linear elastic axial stiffness of the actuator.

For austenite-martensite transformation, the following evolution equation is obtained using relation (2) in equation (7):

$$\dot{\sigma}_S = K\frac{\left[\alpha\, a_M\,(1\text{-}\beta) - \Xi\dot{T}\right]}{\left[1 + K\,\alpha\, b_M\,(1\text{-}\beta)\,\mathrm{sign}(\sigma)\right]}\dot{T} \quad \text{for } |\sigma| \geq \sigma_M \tag{8}$$

For the reverse transformation, using relation (3) in equation (7), it is obtained,

$$\dot{\sigma}_S = K \frac{\left[\alpha\, a_A\, \beta - \Xi \dot{T}\right]}{\left[1 + K\, \alpha\, b_A\, \beta\, \text{sign}(\sigma)\right]} \dot{T} \qquad \text{for } |\sigma| \leq \sigma_A \qquad (9)$$

An iterative predictor-corrector numerical procedure is used to solve the governing equations. The procedure considers a thermoelastic predictor step where no transformation takes place, that is, $\dot{\beta} = 0$. Next, an iterative integration scheme is used to obtain σ_S and β. The process must be repeated until convergence is achieved.

Numerical Simulations

A working device that has been successfully tested in space (Lucy *et al.*[4]) is chosen in the numerical simulations. This device has a Nitinol actuator with 25mm length, 6.6mm inside diameter and 12.7mm outside diameter. A Titanium 318 (6% Al, 4% V) bolt with a ¼ in (6.35mm) diameter and 50mm length is considered. The bolt has a 1.11mm deep notch with 0.25mm radius.

The actuator is pre-compressed and, as a consequence, a 2.5% residual strain is obtained. It guarantees 100% of martensitic phase (M-). A heater with a silicon rubber insulation and adhered to Nitinol cylinder furnishes 120 kW/m^2, which is sufficient to promote a temperature rise of 100^{0}C. Material parameters are presented in Tab. 1 (Jackson *et al.*[3]) and Tab. 2 (Smithells[8]).

Table 1: Material Parameters. Nitinol SMA actuator.

E_S (GPa)	α(GPa)	Ξ(KPa)	M_s (^{0}C)	A_s (^{0}C)
60	1.25	642	20	50

A_M (^{0}C^{-1})	b_M (MPa^{-1})	a_A (^{0}C^{-1})	b_A (MPa^{-1})
1.100	0.080	1.100	0.080

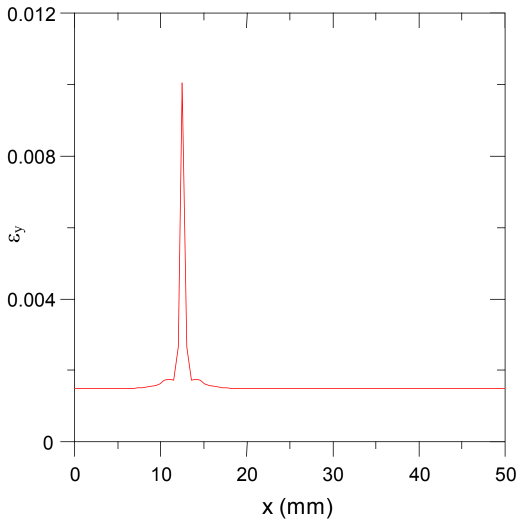
Table 2: Material Parameters. Titanium bolt.

E_B (GPa)	σ_Y (GPa)	σ_U (GPa)	Rupture Elongation (%)
106	1.05	1.15	4.0

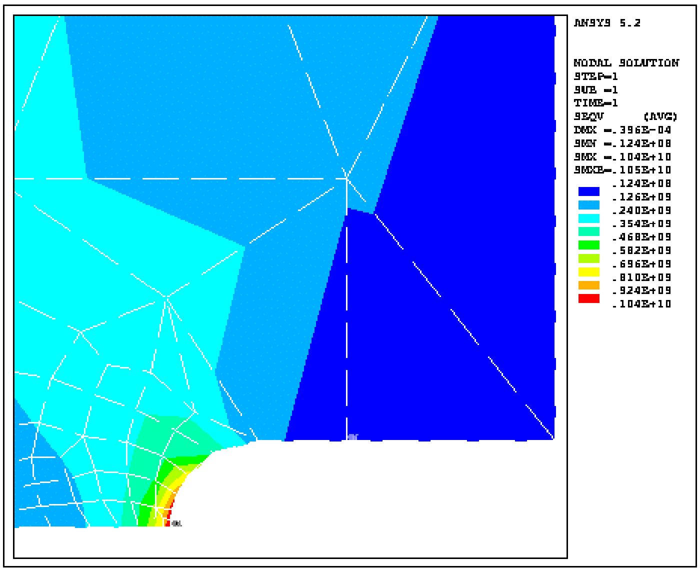
ANSYS/ED 5.2 is used on Finite Element simulations to determine bolt response. By considering an elastic analysis, a linear relationship between force and displacement is observed for all stresses studied. Indeed, a constant stiffness of 63 MN/m is adopted in the following analysis.

First, load resistance during launch is analyzed by considering a force P = 5KN applied to the bolt (Busch *et al.*[2]). Fig. 3a shows axial strain over the bolt length. Strains are concentrated near the notch as it was expected. Figure 3b shows von Mises equivalent stresses in the bolt notch region. In a small region, the stress almost reaches the yielding limit (σ_Y). Stress concentration factor near 3 is observed.

Now, by heating SMA actuator, release procedure is simulated. Figure 4 shows force, displacement and martensitic fraction evolution with temperature variation. Phase transformations induce actuator strain recovery which promotes the release by loading the notched bolt until it breaks.



(a)



(b)

Figure 3: Resistance to launch load. (a) Axial strain distribution over the bolt length; (b) von Mises stresses on the bolt notch.

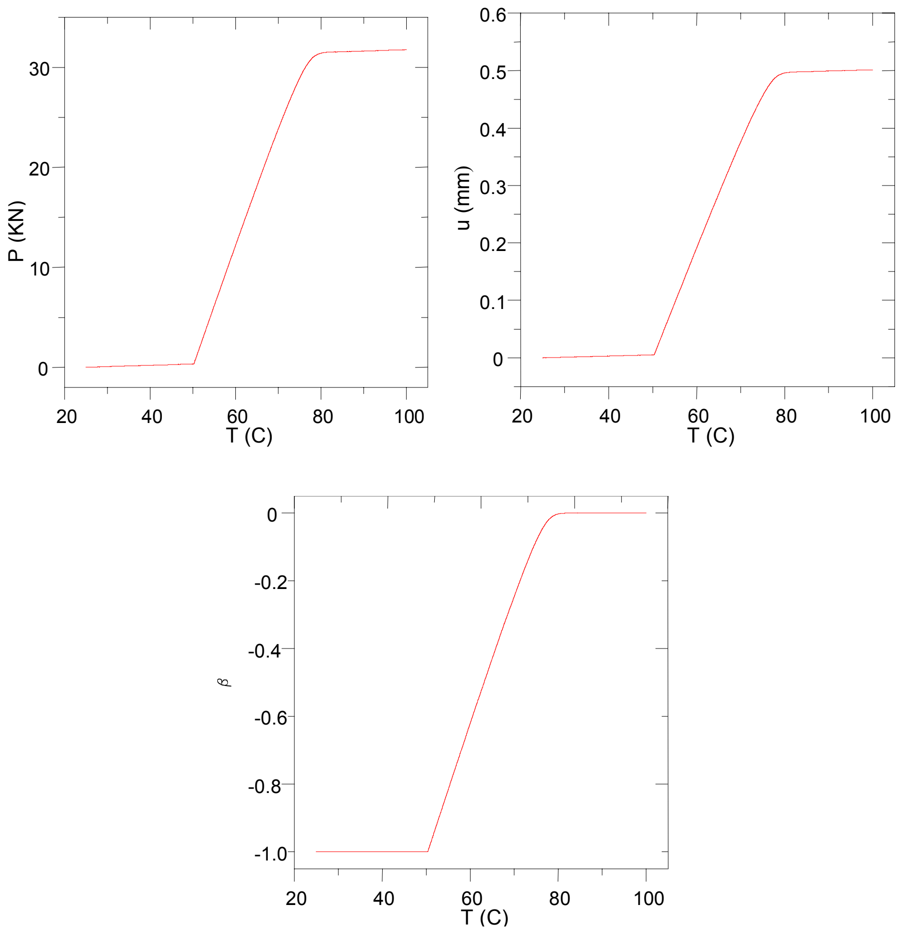
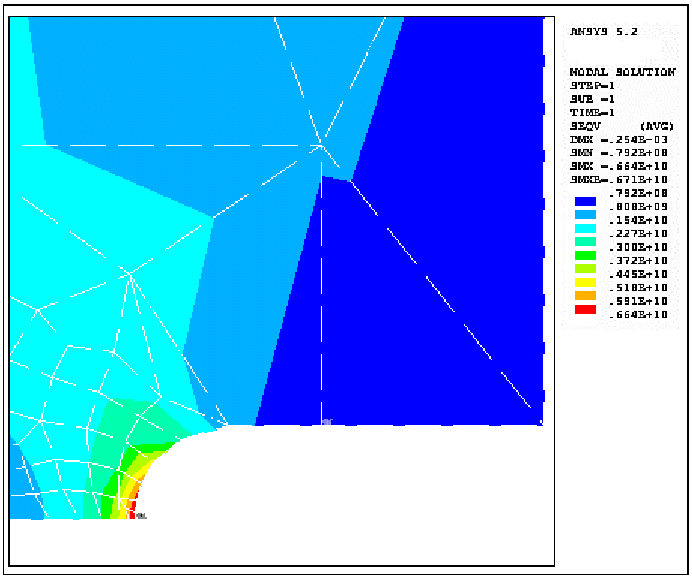
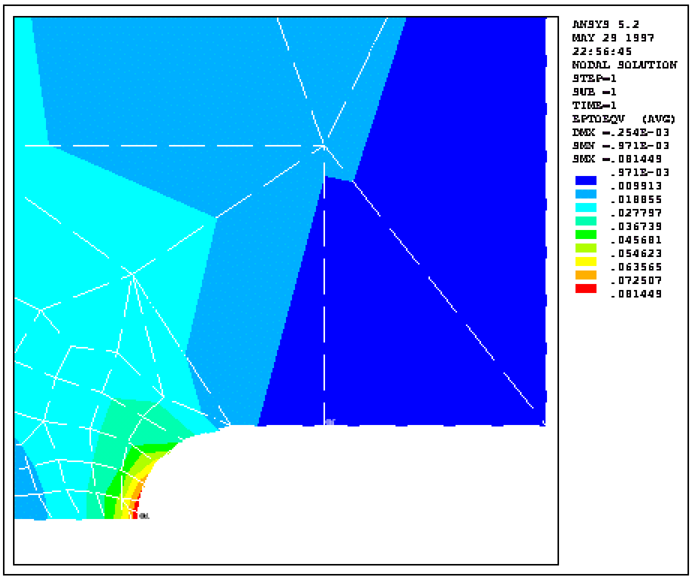


Figure 4: Evolution of Force, displacement and martensitic fraction during release.

By considering the maximum force produced by the actuator, it is possible to analyze bolt response on release procedure. Figure 5 shows von Mises equivalent stresses and strain for P = 32KN. An elastic finite element analysis is developed and maximum values of 6.6 GPa and 8.2% , respectively, are observed at the notch. Actually, the bolt experiments plastic deformations, but the elastic analysis furnishes a simple and conservative way to simulate the device behavior. An elasto-plastic analysis will predict lower stresses and higher strains.



(a)



(b)

Figure 5: Bolt notch response for release load. (a)von Mises stresses and (b) strain.

Conclusions

Release device is an important example of a task usually executed by pyrotechnic mechanisms. Many aerospace applications like satellite solar panels deployment or weather balloon separation need a release device. Several incidents, where pyrotechnic mechanisms could be responsible for spacecraft failure, have been encouraging new designs for these devices. This paper presents the modeling and simulation of release devices using SMAs, specifically, Frangibolt. Despite the simplicity of the model proposed, it predicts results which are consistent with experimental requires. This analysis may contribute to improve Frangibolt design. The proposed model can be improved by considering an elasto-plastic analysis.

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Resumo

Diversas aplicações aeroespaciais, como a abertura de painéis solares ou a recuperação do instrumental de balões meteorológicos, dependem da atuação de dispositivos de separação. Tradicionalmente, empregam-se mecanismos pirotécnicos que apresentam problemas associados a segurança, confiabilidade e transmissão de choque. A falha de alguns dispositivos pirotécnicos vêm motivando o desenvolvimento de mecanismos alternativos baseados em outros princípios. O Frangibolt é um mecanismo não-explosivo composto de um parafuso comercial e de uma luva fabricada de uma liga com memória de forma (SMA). Este trabalho apresenta a modelagem e a simulação do dispositivo de separação Frangibolt. Espera-se que a análise possa contribuir para otimizar o projeto deste dispositivo.

Palavras-chave
Ligas com Memória de Forma, Aplicações Aerospaciais,
Dispositivo de Separação, Frangibolt.

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