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Evaluation of Precision-Cast TiNi Shape Memory Alloy Brain Spatula

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Abstract In order to develop a brain spatula made of a shape memory alloy (SMA), this paper discusses the bending characteristics of a new brain spatula precision-cast in a TiNi SMA. Based on the yield stress and the modulus of elasticity of the copper and the TiNi SMAs, the bending deformation properties of the SMA-brain spatula were estimated by assuming the condition to use the brain spatula as the bending of the strip cantilever. With respect to the SMA-brain spatula for the same length and width as the existing copper one, if the thickness of the conventional rolled-SMA spatula is 1.3 times as large as that of the existing copper-brain spatula, the SMA spatula can hold the same bending rigidity and can be bent by a smaller force than the existing copper one. If the thickness of the new cast-SMA spatula is 1.2 times as large as that of the existing-copper spatula, the SMA spatula can hold the same bending rigidity and can be bent by the same force as the existing copper one.

1. Introduction

The shape memory effect (SME) and superelasticity (SE) are characteristic behaviors of a shape memory alloy (SMA). A strain of several percent can be recovered by heating in the case of the SME or unloading in the case of SE. These behaviors occur due to the martensitic transformation (MT) and its reverse transformation. The large recovery stress and great amounts of energy dissipation and storage associated with the MT are effectively exploited in an SMA [1]-[5]. The development of applications for SMAs as intelligent materials has therefore attracted worldwide attention. SMAs are now in use across wide fields of industry, electrical manufacturing, and medical and leisure technologies, to name only a few.

A brain spatula or brain retractor is an instrument used in surgery to hold a brain incision open while a deep cerebral tumor is operated on. A schematic image of how this is done is shown in Fig. 1. As shown, the spatula is used in a bent form, fitting the shape and depth of the individual brain. After the operation, the spatula is struck with a miniature hammer to return it to its original flat form, after which it is sterilized by heating and is then ready for reuse. The usual material for brain spatulas hitherto has been copper, but owing to the irrecoverable loss of evenness that develops on the copper surface after each use, in practice the instrument has to be disposed of after being used only a few times. If an SMA material is used instead, the original flat shape can be restored automatically and precisely through the working of the SME during the sterilization heating in the autoclave. This not only saves time and dispenses with the need for hammering, but also

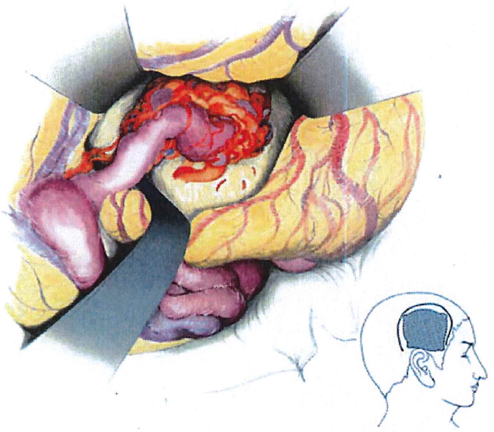

Fig. 1. Illustration of a brain spatula in surgical use

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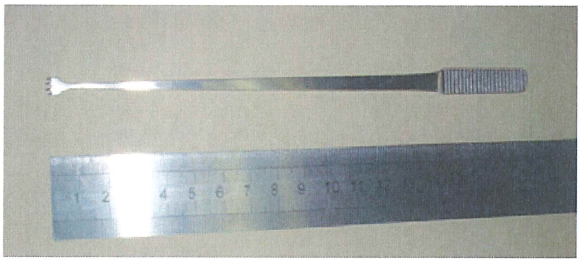
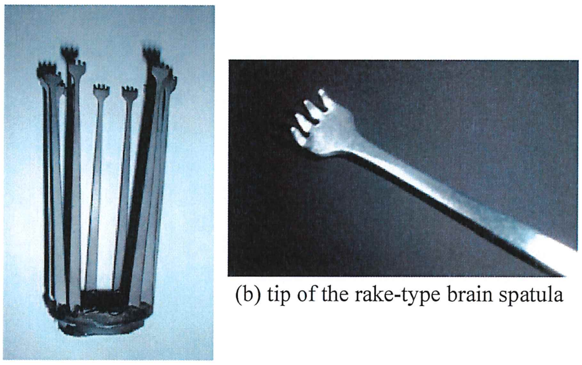


(a) whole rake-type brain spatula against a centimeter



(b) tip of the rake-type brain spatula

(c) batch of brain spatulas just after precision casting

Fig. 2. Examples of precision-cast TiNi SMA brain spatulas; (a) whole rake-type brain spatula against a centimeter scale, (b) tip of the rake-type brain spatula, (c) batch of brain spatulas just after precision casting

means that the unevenness left from plastic deformation is much reduced so that the spatula can be reused over and over.

The instruments treated in this study have been recently developed and are precision-cast in a lost-wax process of the self-combustion high-temperature synthesis method [6]. The brain spatula needs to form itself into unique shapes according to the brain configurations of individual patients and, as can be seen from the examples in Fig. 2, the spatulas themselves also come in intricate forms that are a challenge to create in the TiNi SMA material. The precision casting technique makes it much easier for these tools to be manufactured.

The conditions required of a brain spatula are, first, that it can be bent to any desired shape to fit the brain being operated on and, second, that it should have sufficient rigidity to be able to keep the brain incision open during the operation. These requirements can be specified in terms of the bending deformation properties of the instrument, including its bending rigidity. This paper is the first reported study of the plane bending properties of a TiNi SMA considered as the material for a brain spatula.

For the present study, in pursuit of the development of the SMA brain spatula, tension tests were conducted to examine stress-strain relations in three materials: the newly introduced cast TiNi SMA, a TiNi SMA of the conventional rolled type, and copper of the type used in brain spatulas up until now. The shape and dimension requirements of an SMA brain spatula were investigated on the basis of the bending deformation properties of a strip cantilever.

2. Experimental method

2.1. Materials and specimens

The materials used in the experiment were a new-type cast Ti-49.7at%Ni SMA, a conventional rolled Ti-50.0at%Ni SMA, and copper as used in brain spatulas hitherto. The new cast SMA was produced by precision casting using a lost-wax process from a self-combustion high-temperature synthesis method [6]. Samples of the cast and rolled SMAs were shape-memorized by fixing them in a flat plane for 40 min at a furnace temperature of 753 K and then quenching them in water. The starting and finishing temperatures for the MT of the SMAs, M_s and M_f, and those for the reverse transformation, A_s and A_f, were obtained from the DSC (differential scanning calorimetric) tests. The values obtained were $M_s = 326$ K, $M_f = 312$ K, $A_s = 342$ K, $A_f = 365$ K for the rolled SMA and $M_s = 358$ K, $M_f = 283$ K, $A_s = 314$ K, $A_f = 386$ K for the cast SMA. The specimens used in the tension tests were the uniform rectangular bars with a thickness $t = 1.0$ mm, width $w = 1.2$ mm and length $l = 160$ mm for the rolled and cast SMAs, with corresponding values of $t = 1.0$ mm, $w = 8.5$ mm and $l = 140$ mm for the copper.

2.2. Experimental apparatus

An SMA characteristic-testing machine was used for the tension test [7]. The testing machine was composed of a tension control for loading and unloading and a heating-cooling device to control temperature. Displacements of the specimen were measured using an extensometer with a gauge length of 50 mm.

2.3. Experimental procedure

The tension tests were carried out under a constant strain rate in air at room temperature below the M_f point of the SMA bars. Since the yielding of the SMA occurs under low stress in the M-phase, the SMA-brain spatula can be bent with a very small force. In the case of SMA bars in the M-phase, a residual strain appears after unloading. SMA bars showing the residual strain were heated up to temperatures above the A_f point under no load. In this heating process of the SMA bars, the residual strain was found to diminish due to the reverse transformation between the A_s and A_f points.

3. Deformation properties of materials used for brain spatula

3.1. Tensile deformation properties

The stress-strain curves of the copper, the rolled and the cast SMAs obtained from the tension test under a strain rate of $d\varepsilon/dt = 2\times10^{-4}$ s^{-1} are shown in Fig. 3. As can be seen in Fig. 3, a linear elastic deformation occurs in the initial loading stage and yielding occurs thereafter. The modulus of elasticity E determined from the slope of the initial stress-strain curve is 40 GPa for the rolled SMA, 54 GPa for the cast SMA and 95 GPa for the copper. Approximating the elastic and yield regions of the stress-strain curves to two straight lines, the yield stress σ_M was determined from the intersection of these lines. This gave a value of 68 MPa for the rolled SMA, 168 MPa for the cast SMA and 240 MPa for the copper. In the case of the copper, the deformation seen at strain levels of above 0.2 % occurs due to plastic deformation with dislocations. For example, in the unloading process from a strain of 4 %, there is a strain recovery of 0.25 % corresponding to the elastic deformation, leaving the residual strain as permanent strain. In the cases of the SMAs, however, since the material is in the M-phase at room temperature below the M_f point, yielding occurs due to rearrangements in the M-phase. In the unloading process from the same strain of 4 %, there is a strain recovery of 0.6 % for the rolled, and 0.8 % for the cast SMA, leaving the residual strains of 3.4 % and 3.2 % respectively after unloading.

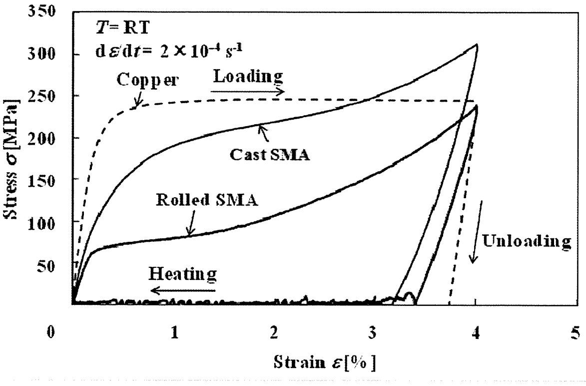


Fig. 3. Tensile stress-strain curves for copper, rolled SMA and cast SMA as materials for brain spatulas

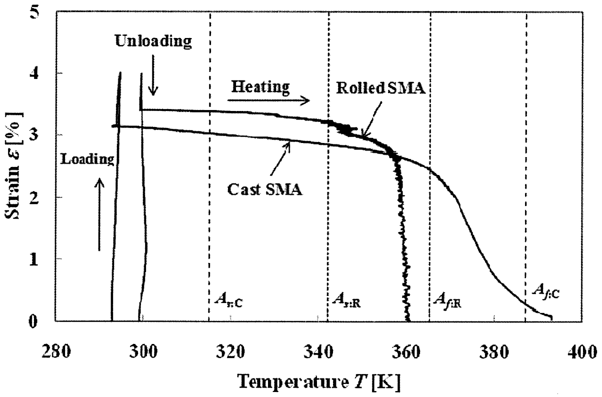


Fig. 4. Strain-temperature curves for rolled and cast SMA in tension, with unloading followed by heating without loading

The relationships between strain and temperature for the cast and rolled SMAs, obtained from tension tests with unloading followed by heating in the absence of load, are shown in Fig. 4. The symbols $A_{s:C}$, $A_{s:R}$, $A_{f:C}$ and $A_{f:R}$ in Fig. 4 represent the starting and finishing temperatures for the reverse-transformation in the cases of the cast and rolled SMAs, respectively. In the heating process under no load, strain begins to recover gradually around A_s and disappears altogether around A_f. The SME behind this strain recovery occurs as a result of the reverse transformation from the M-phase to the parent (austenite) phase.

3.2. Comparison of characteristic values for deformation

Table 1 sets out the values of the modulus of elasticity E, the yield stress σ_M, the yield strain ε_M and the hardening modulus k for the copper, the rolled and the cast SMAs materials, as obtained from the tension tests. As can be seen, both the modulus of elasticity and the yield stress are lower for the rolled and the cast SMAs than for the copper. These differences account for the residence to bending deformation in the SMA materials, and also for the bending rigidity which allows the brain incision to be held open in a particular shape during the operation. In the next section, the bending deformation properties of brain spatulas made of these materials will be discussed.

Table 1. Values of modulus of elasticity, yield stress, yield strain and hardening modulus for copper, rolled SMA and cast SMA

Materials	Copper	Rolled SMA (M-phase)	Cast SMA (M-phase)
Modulus of elasticity E [GPa]	95	40	54
Yield stress σ_M [MPa]	240	68	168
Yield strain ε_M [%]	0.25	0.17	0.34
Hardening modulus k [GPa]	0	2.6	2.5

4. Bending characteristics of copper and SMA brain spatulas

In order to design an SMA brain spatula, it is important to evaluate the force required for bending of the spatula in operational use and the bending rigidity required for brain incision to be held open during the operation. With a focus on these two bending deformation properties in spatulas made of copper and SMA, the required specifications for an SMA brain spatula will be clarified. Conceiving of the existing type of brain spatula as a bendable cantilever made of a strip of material with a uniform rectangular cross-section, the length of the strip can be expressed by l, the width of the cross-section by w and the thickness by t.

4.1. Bending rigidity required to hold the brain spatula in its bent form

In order to maintain the chosen displacement in the part of the brain that is opened during the operation, it is required that the brain spatula should remain stable in its bent form (see Fig. 1). This requirement can be quantified in terms of the maximum permitted deflection in a cantilever made of the specified materials. Let us consider, in particular, the conditions required in each case for obtaining the same maximum deflection y_{max} in response to the same force F applied at the top of the cantilever. The maximum deflection of the cantilever y_{max} can be expressed using the second moment of area $I_z = wt^3/12$ from the theory of elasticity as follows

$$y_{\max} = \frac{Fl^3}{3EI_Z} = \frac{4Fl^3}{Ewt^3} \tag{1}$$

Assuming that this maximum deflection *ymax* in strips subjected to the same force F coincides for the copper and SMA materials, the following equation is obtained

$$y_{\max} = \frac{4Fl_{Cu}^{\ 3}}{E_{Cu}w_{Cu}t_{Cu}^{\ 3}} = \frac{4Fl_{SMA}^{\ 3}}{E_{SMA}w_{SMA}t_{SMA}^{\ 3}} \tag{2}$$

From the practical point of view of a brain operation, the width w and the length l of an SMA brain spatula are expected to offer the same values as for a conventional spatula made of copper. Therefore, it is appropriate to assume that the length and width dimensions of both kinds of spatula will coincide, leaving only the thickness t to differ. The thickness for the SMA spatula t_{SMA} can be found from Eq. (2) as follows

$$t_{SMA} = t_{Cu}\sqrt[3]{\frac{E_{Cu}}{E_{SMA}}} \tag{3}$$

If the values for the modulus of elasticity shown for the copper and SMA materials in Table 1 are now substituted in Eq. (3), the bending rigidities of the three types of spatulas will be found to coincide when the rolled SMA spatula has a thickness of 1.3 times, and the cast SMA spatula a thickness of 1.2 times that of the copper spatula. These are the conditions, in other words, in which the same deflection and bending rigidity can be obtained from the SMA brain spatulas as from the copper one.

4.2. Force required to bend brain spatula

In a brain operation, the surgeon has to bend the spatula to fit the exact shape and depth of the part of the brain being opened. The force required to bend the brain spatula is evaluated as the force applied at the top of the cantilever to obtain the required maximum bending strain. As shown in Fig. 5a, the yield (transformed) regions of the strip during bending occur at the inner and outer surfaces of the cantilever. A schematic stress-strain diagram and the distributions of bending strains and stresses in the strip are shown in Figs. 5b, and 6, respectively. In Fig. 5b, it is assumed that the yielding region can be expressed by the linear hardening with a hardening modulus k while the yield stress and yield strain are expressed by σ_M and ε_M, respectively. In these figures, the maximum bending stress and strain are denoted by σ_m and ε_m,

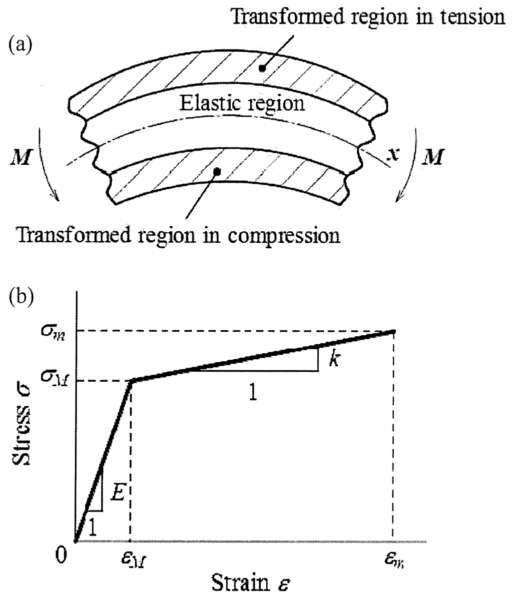


Fig. 5. (a) Elastic and transformed regions of the specimen in bending; (b) stress-strain diagram

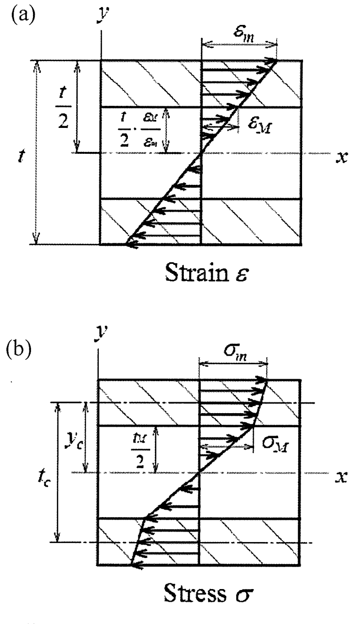


Fig. 6. Bending strain (a) and stress (b) distribution in the specimen

respectively. It is assumed that the yield stress σ_M is the same in tension as in compression.

Let us first consider the bending moment M_e required to produce the elastic region of the strip in bending. The thickness of the elastic region t_M is $t_M = (\varepsilon_M / \varepsilon_m)t$. Since the maximum bending stress in the elastic region σ_{max} is the same as the yield stress σ_M, the bending moment required for the elastic region M_e is $M_e = \sigma_M Z$, where Z denotes the section modulus and $Z = wt_M^2/6$. Accordingly, the bending moment Me for the elastic region is

$$M_e = \frac{\sigma_M w t^2}{6}\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2 \tag{4}$$

Next, let us turn our attention to the bending moment M_y required to create the yield (transformed) region of the strip. The center of the yield region y_c from the neutral axis z is calculated as

$$y_c = \frac{t_c}{2} = \frac{t}{4}\left(1+\frac{\varepsilon_M}{\varepsilon_m}\right) \tag{5}$$

The area A_y of the yield region in the tension side of the cross section is

$$A_y = \frac{wt}{2}\left(1-\frac{\varepsilon_M}{\varepsilon_m}\right) \tag{6}$$

Considering the stress distribution in the yield region and the symmetric match between the tension and compression sides, the bending moment M_y required to create the yield region is obtained as follows

$$M_y = \frac{1}{2}(\sigma_M+\sigma_m)A_y t_c = \frac{1}{8}\left[2\sigma_M + k(\varepsilon_m-\varepsilon_M)\right]wt^2\left[1-\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2\right] \tag{7}$$

The total bending moment M required to bend the brain spatula is the sum of the bending moment M_e for the elastic region and the bending moment M_y for the yield region

$$M = M_e + M_y = \frac{wt^2}{24}\left\{2\sigma_M\left[3-\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2\right]+3k(\varepsilon_m-\varepsilon_M)\left[1-\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2\right]\right\} \tag{8}$$

Since the bending moment $M = Fl$, the force required is

$$F = \frac{wt^2}{24l}\left\{2\sigma_M\left[3-\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2\right]+3k(\varepsilon_m-\varepsilon_M)\left[1-\left(\frac{\varepsilon_M}{\varepsilon_m}\right)^2\right]\right\} \tag{9}$$

The condition that the forces required to bend a copper spatula with $k = 0$ and an SMA spatula coincide can be expressed as follows

$$F = \frac{\sigma_{MCu} w_{Cu} t_{Cu}^{2}}{12 l_{Cu}} \left[3 - \left(\frac{\varepsilon_{MCu}}{\varepsilon_{mCu}} \right)^{2} \right] = \frac{w_{SMA} t_{SMA}^{2}}{24 l_{SMA}} \left\{ \begin{aligned} & 2\sigma_{MSMA} \left[3 - \left(\frac{\varepsilon_{MSMA}}{\varepsilon_{mSMA}} \right)^{2} \right] \\ & + 3k_{SMA} \left(\varepsilon_{mSMA} - \varepsilon_{MSMA} \right) \left[1 - \left(\frac{\varepsilon_{MSMA}}{\varepsilon_{mSMA}} \right)^{2} \right] \end{aligned} \right\} \qquad (10)$$

If the length l, the width w and the maximum bending strain ε_m of both spatulas coincide only the thickness to differ, the thickness of the SMA brain spatula is

$$t_{SMA} = t_{Cu} \sqrt{ \frac{ 2\sigma_{MCu} \left[3 - \left(\frac{\varepsilon_{MCu}}{\varepsilon_m} \right)^{2} \right] }{ \begin{aligned} & 2\sigma_{MSMA} \left[3 - \left(\frac{\varepsilon_{MSMA}}{\varepsilon_m} \right)^{2} \right] \\ & + 3k_{SMA} \left(\varepsilon_m - \varepsilon_{MSMA} \right) \left[1 - \left(\frac{\varepsilon_{MSMA}}{\varepsilon_m} \right)^{2} \right] \end{aligned} } } \qquad (11)$$

The yield stress σ_M, the yield strain ε_M and the hardening modulus k for the three types of materials are shown in Table 1. Using these values, the thickness of the SMA brain spatula t_{SMA} can be obtained from Eq. (11). The calculated relations between the thickness ratio t_{SMA}/t_{Cu} and the maximum bending strain ε_m are shown in Fig. 7. If the material of the thickness t_{SMA} shown in this figure is used, an SMA spatula can be bent by the same force as that required for a conventional copper spatula. As can also be seen from Fig. 8, the maximum bending strain ε_m exerts very little effect on the ratio of t_{SMA} to t_{Cu} except in an area of small ε_m values close to the yield strain ε_M. When the thicknesses of the rolled and cast SMA spatulas are 1.85 times and 1.2 times that of the copper spatula, respectively, the SMA spatula can be bent by applying the same force as with an existing copper spatula.

4.3. Shape of SMA brain spatula

The discussion in Sections 4.1 and 4.2 will have made clear that if the length and the width of a rolled SMA brain spatula are the same as those of the existing copper type while the thickness is 1.3 times as large, the rolled SMA spatula is capable of the same bending rigidity and can be easily bent using a smaller force than required for the copper one. Similarly, if the thickness of the cast SMA spatula is 1.2 times that of the copper one, the cast SMA spatula is capable of the same bending rigidity and can be bent by the same force as an existing copper one.

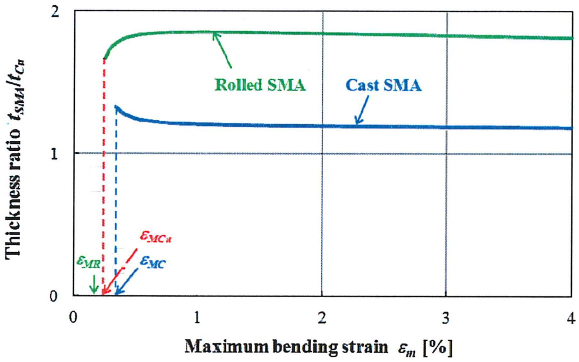


Fig. 7. Relationship between the thickness ratio t_{SMA}/t_{Cu} and the maximum bending strain ε_m calculated from Eq. (11)

5. Conclusions

In order to develop the SMA-brain spatula, the mechanical characteristics of the TiNi cast- and rolled-SMAs and the copper one used for the brain spatula were compared based on the tensile deformation properties, and the characteristics of the SMA-brain spatula were discussed. The results obtained can be summarized as follows.

(1) Based on the yield stress and the modulus of elasticity of the copper and the TiNi SMAs, the bending deformation properties of the SMA-brain spatula were estimated by assuming the condition to use the brain spatula as the bending of the strip cantilever. With respect to the SMA-brain spatula for the same length and width as the existing copper one, if the thickness of the conventional rolled-SMA spatula is 1.3 times as large as that of the existing copper-brain spatula, the SMA spatula can hold the same bending rigidity and can be bent by a smaller force than the existing copper one. If the thickness of the new cast-SMA spatula is 1.2 times as large as that of the existing-copper spatula, the SMA spatula can hold the same bending rigidity and can be bent by the same force as the existing copper one.

(2) The above mentioned characteristics of the SMA-brain spatula obtained in this study will be substantially applied to the development not only for the brain spatula but also

for other retractors and instruments used in other surgery operations.

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