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Finite element modeling of shape memory alloy stent insertion in the vessel with consideration of vessel damage

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ABSTRACT: One of the common methods to resolve artery stenosis is the insertion of a shape memory alloy stent in the artery. The use of shape memory alloys in the manufacturing of self-expandable stent has expanded because of the superelastic behavior of this alloy. In this paper, we simulated a shape memory alloy stent insertion in an artery to explore stress and damage effects arising from the stent insertion on the artery by using ABAQUS software. To simulate the mechanical behavior of artery, we considered the effect of the inelastic arterial properties (stress softening and recoverable inelastic deformation) that activated under supraphysiological loading in the stenting process, and to simulate stent behavior, the Souza model is used. These two models were applied in ABAQUS by UMAT codes. By using the damage model, the amount of damage in the artery, which is one of the factors of restenosis, is investigated. Also, in this paper, we have used real diseased artery geometry, which was specified from high-resolution magnetic resonance images, therefore the analysis is more in line with reality and it is possible to determine the location of the maximum stress and damage in the artery.

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1. INTRODUCTION

One way to treat atherosclerosis is the insertion of a Shape Memory Alloy (SMA) stent, which is a self-expandable stent, in the artery. A self-expandable stent is compressed by a crimper, and when the crimper is retracted, the stent expands by itself. Different constitutive models have been provided to explain the behavior of shape memory alloy materials [1-4]. The modeling of the geometry and mechanical behavior of the artery are important issues to predict the accurate effects of the stent on the artery. In different studies, different assumptions were applied for modeling the artery to simplify this simulation. The majority of studies employed a simplified cylindrical shape for artery [5-8] which is not a realistic assumption. Some studies focused on a more real geometry of the stenosed artery [9, 10]. However, they employed a hyperelastic constitutive model for the arterial tissue.

In this paper, it is aimed to investigate the effects of the SMA stent on real geometry artery by considering an inelastic model with stress softening and permanent deformation behavior to simulate the mechanical behavior of the artery.

2. METHODOLOGY

To determine the mechanical behavior of the artery we use an inelastic model [11]; material parameters of the artery layers and plaque are listed in Table 1. It should be noted that the dissipation and damage effects in the plaque are disregarded.

The constitutive mechanical behavior of shape memory alloy stent is based on Souza model [2] and its parameters are listed in Table 2 [1].

In the present study, we use an individual human stenosis artery. The inner and outer diameter and the strut width of the stent are 5, 5.1, and 0.1 mm. The geometry of the stent and artery are presented in Fig. 1.

In the loading step, the stent with a diameter of 5mm is squeezed to the diameter of 2mm. After removing the applied pressure, the stent expands to its original shape. Two ends of the stent are constrained in the circumferential direction. To avoid moving the stent in the longitudinal direction, the stent is constrained at one end in the longitudinal direction. Three dimensional eight-node linear, hybrid elements (C3D8H) are put to use for the artery and stent.

3. RESULTS AND DISCUSSION

In Fig. 2 the stress and strain of the artery are shown, and both the loading and unloading steps are considered. As shown, by unloading, the amounts of stress and strain decrease, but they are not totally eliminated. Such residual effects are important to predict other behaviors of the artery.

Maximum damage developed in the artery by both the shape memory alloy and Stainless Steel (SS) stent is plotted in Fig. 3. As shown, with a similar displacement of stents, the damage which is caused by SS stent is higher; therefore, shape memory alloy is better than stainless steel to manufacture stents.

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Table 1. Material parameters of the hyperelastic -damage (inelastic) model to determine the mechanical behavior of the artery [11]

	μ (MPa)	k_1 (MPa)	k_2	κ	θ	μ^* (MPa)	k_1^* (MPa)	k_2^*	κ^*	r_1	m_1 (MPa)	m_2
Intima	0.017	0.263	41.191	0.3	90	0.001292	0.014591	0	0	1.49	0.0192	3
Media	0.012	0.059	3.871	0.02	45.3	0.000098	0.000611	0.665	0.29	1.44	0.0077	3.32
Adventitia	0.008	0.222	9.948	0.23	53.1	0.001206	0.000001	0.011	0.33	4	0.001	4
Plaque	0.0075	3.5806	12	0.225	58	-	-	-	-	-	-	-

Table 2. The material parameters of Souza model to determine the mechanical behavior of the stent [1]

Parameter	Amount of parameter
E (MPa)	53000
ν	0.33
h (MPa)	1000
β (MPa/°C)	6.1
T^* (°C)	-30
R (MPa)	100
ε_L	5.6%

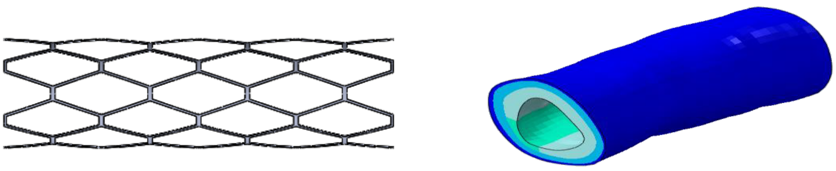

Fig. 1. The geometry of the stent and artery

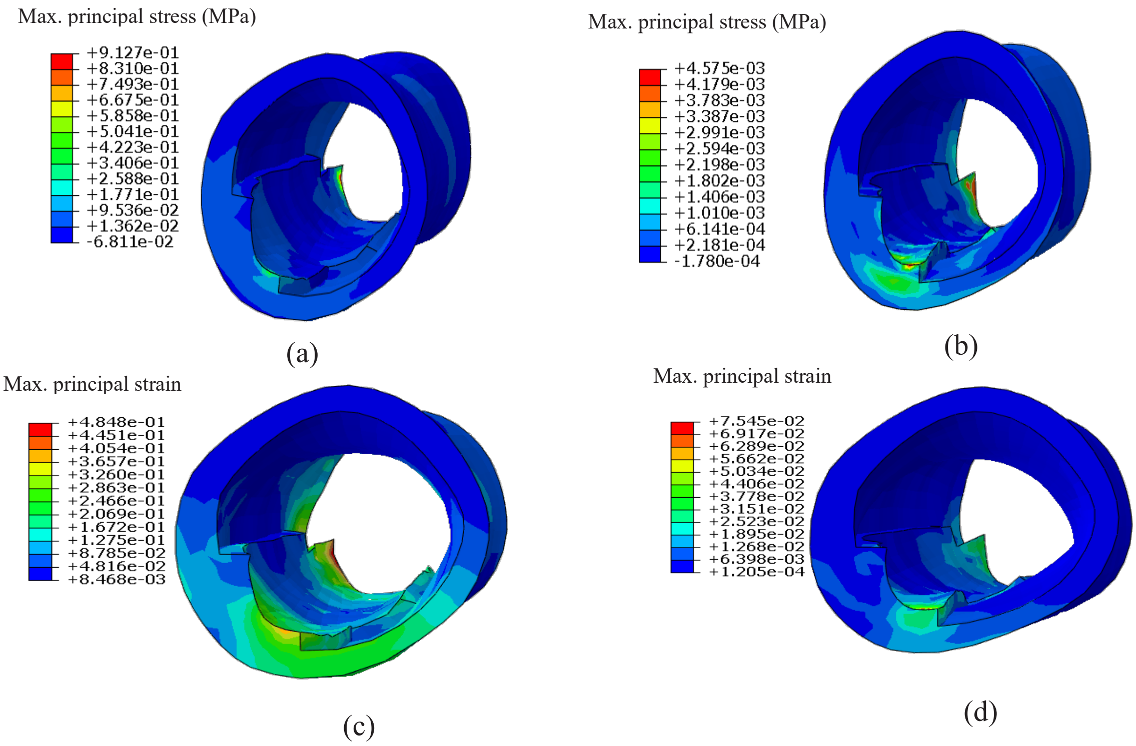

Fig. 2. (a) The stress of the artery after the artery expansion (b) The stress of the artery after the artery unloading (c) The strain of the artery after the artery expansion (d) The strain of the artery after the artery unloading

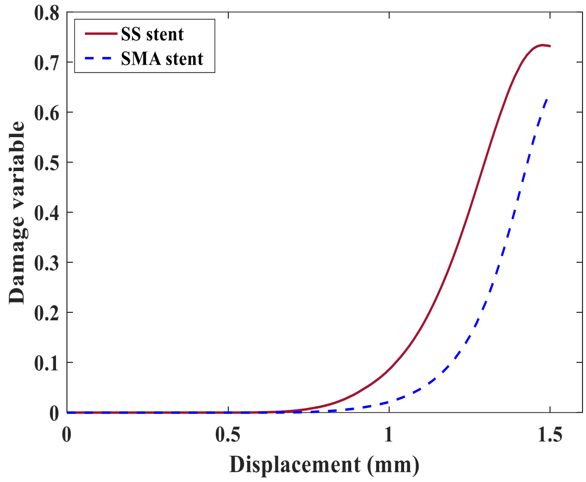

Fig. 3. Damage diagram of the artery due to the expansion of the SMA and SS stent

4. CONCLUSIONS

Stent insertion in the artery is one of the common treatments for atherosclerosis. Previous studies were based on simplified models for arterial tissue. In this paper, we simulated the insertion of a shape memory alloy stent in a real-geometry artery and inelastic arterial behavior. Finally, the maximum stress in arterial layers which is the main cause of the surgically-induced damage in arterial tissue was presented, also the damage diagram of the artery is plotted. Such simulations can be useful to compare different stents to minimize artery damage and choose the best material for manufacturing stents.

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