Medical Engineering & Physics 36 (2014) 1455–1463

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Monolithic superelastic rods with variable flexural stiffness for spinal fusion: Modeling of the processing–properties relationship

Yann Facchinello[a,b], Vladimir Brailovski[a,b,*], Yvan Petit[a,b], Jean-Marc Mac-Thiong[b,c]

[a] École de technologie supérieure, 1100 Notre-Dame Street West, Montreal, QC, Canada H3C 1K3
[b] Research Center, Hôpital du Sacré-Cœur de Montréal, 5400, boul. Gouin West, Montreal, QC, Canada H4J 1C5
[c] Department of Surgery, Faculty of Medicine, University of Montreal, Pavillon Roger-Gaudry, S-749, C.P. 6128, succ. Centre-ville, Montreal, QC, Canada H3C 3J7

ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form 16 June 2014
Accepted 20 July 2014

Keywords:
Spinal fusion
Instrumentation with variable flexural stiffness
Shape memory alloy
Local Joule-heating annealing
Finite element analysis

ABSTRACT

The concept of a monolithic Ti–Ni spinal rod with variable flexural stiffness is proposed to reduce the risks associated with spinal fusion. The variable stiffness is conferred to the rod using the Joule-heating local annealing technique. The annealing temperature and the mechanical properties' distributions resulted from this thermal treatment are numerically modeled and experimentally measured. To illustrate the possible applications of such a modeling approach, two case studies are presented: (a) optimization of the Joule-heating strategy to reduce annealing time, and (b) modulation of the rod's overall flexural stiffness using partial annealing. A numerical model of a human spine coupled with the model of the variable flexural stiffness spinal rod developed in this work can ultimately be used to maximize the stabilization capability of spinal instrumentation, while simultaneously decreasing the risks associated with spinal fusion.

1. Introduction

Spinal disorders can be treated by several means including multisegmental fusion surgery. Rigid posterior instrumentations are commonly used to prevent motion of the instrumented segment and aid fusion healing [1,2]. However, this procedure brings its own problems, including adjacent-level disc disease. Due to the abrupt stiffness variation between the instrumented and intact spinal segments, stresses are increased locally, which is commonly considered as a factor leading to disc degeneration [3]. The use of so-called dynamic stabilization systems have been proposed to lower the stress concentration at the extremities of the implant and to reduce the risk of adjacent segment degeneration [4]. Those "soft" instrumentations are however accompanied by problems such as mechanical failure of the implant or degeneration within the stabilized segment [5,6].

An ideal implant would combine stiff and compliant properties by providing the required stiffness where a strong stabilization is needed while allowing a greater flexural compliance where motion and load-sharing capacity are more important. This complexity of properties can be obtained by different methods including the use of Ti–Ni shape memory alloys. The mechanical properties of these metallic alloys are greatly conditioned by their thermomechanical processing as described by [7–9] and can be finely controlled by local annealing as described by Groh [10] and Mahmud et al. [11]. In has been shown that for the same Ti–Ni alloy, the alloy's elasticity modulus can range from 30 to 60 GPa depending on the thermomechanical processing applied [12]. It has also been shown that monolithic Ti–Ni rods with variable mechanical properties could be produced using localized Joule-heating heat treatment [12]. Different sections of these rods then manifest different behavior, ranging from elastoplasticity to superelasticity and even pseudoplasticity (shape memory), each behavior corresponding to different stiffness. These technological possibilities allow multisegmental monolithic spinal rods to be designed with locally-controlled flexural stiffness, which would combine improved stabilization capacity and reduced stress concentration at the implant extremities.

The main objective of this study is to develop and validate numerical models of the Ti–Ni variable-stiffness spinal rods' processing and behavior, which could ultimately be used in human spine models to find a compromise between the static and the dynamic stabilization capacities of spinal instrumentations.

* Corresponding author at: École de technologie supérieure, Mechanical Engineering, 1100, Notre-Dame Street West, Montreal, QC, Canada H3C1K3.
Tel.: +1 514 396 8594; fax: +1 514 396 8530.
E-mail address: vladimir.brailovski@etsmtl.ca (V. Brailovski).

http://dx.doi.org/10.1016/j.medengphy.2014.07.012

2. Materials and methods

Fig. 1 illustrates the overall path followed in this study. First, a numerical model simulating localized Joule-heating on a 5.5 mm diameter rod is developed and validated by comparing experimental data with calculations. Such a model is found capable of predicting the temperature distribution on a locally-annealed rod as a function of a given electric current intensity–heating time schedule. Next, a series of Ti–Ni specimens are subjected to variable Joule-heating heat treatments and mechanically characterized by tensile testing to produce a set of annealing temperature-dependant stress–strain diagrams (material law). Each stress–strain diagram can then be assigned to a specific annealing temperature. By combining the temperature distribution of the locally-annealed rod and the material law, a numerical model capable of simulating the effect of Joule-heating annealing on the mechanical behavior of Ti–Ni variable-stiffness rods is developed and experimentally validated. The developed numerical tools are then used for two case studies involving: (a) heating strategy optimization, and (b) variable-stiffness rod's flexural behavior prediction.

2.1. Material

The material is an as-drawn (cold worked strain of about 30%) Ti–55.94Ni (wt.%) 5.5 mm—diameter rod supplied by Johnson Matthey (San Jose, CA, USA).

2.2. Joule-heating annealing setup

Joule-heating post-deformation annealing (J-PDA) is performed on a custom-made bench (Fig. 2) using an RE30-170 (Matsusada Precision, Japan) power supply capable of injecting 170 A at 30 V. Temperature is measured either by an E60 (FLIR Systems, USA) thermal imager, or by a K-type thermocouple (TT-K-36-SLE, Omega Eng. Inc, USA.).

2.3. Annealing: Joule-heating induced temperature distribution modeling and validation

Commercial ANSYS 14 finite element analysis (FEA) software is used to create the solid model of the rod and to analyze the effect of Joule-heating on the temperature distribution in the rod. The ANSYS' "Thermal-Electric" (steady-state) and "Transient Thermal" modules are used to simulate the local Joule-heating and its impact on the temperature distribution during annealing. The main inputs of the thermal-electric model are: the geometry and the electrical properties of the rod-electrical contacts assembly, the electrical current intensity, and the thermal exchange conditions with the surroundings. The output of the thermal-electric model is the volume distribution of the Joule heating-induced heat sources. These last data are used in the transient thermal model to calculate the temperature distribution in the rod-contacts assembly as a function of the heating time.

The complete model is a 25 cm long, 5.5 mm diameter rod with two electrical contacts composed of 6652 SOLID226 elements

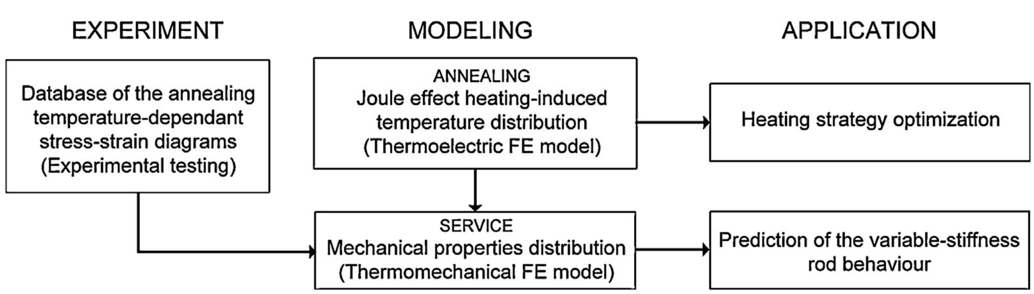

Fig. 1. The path followed in this study.

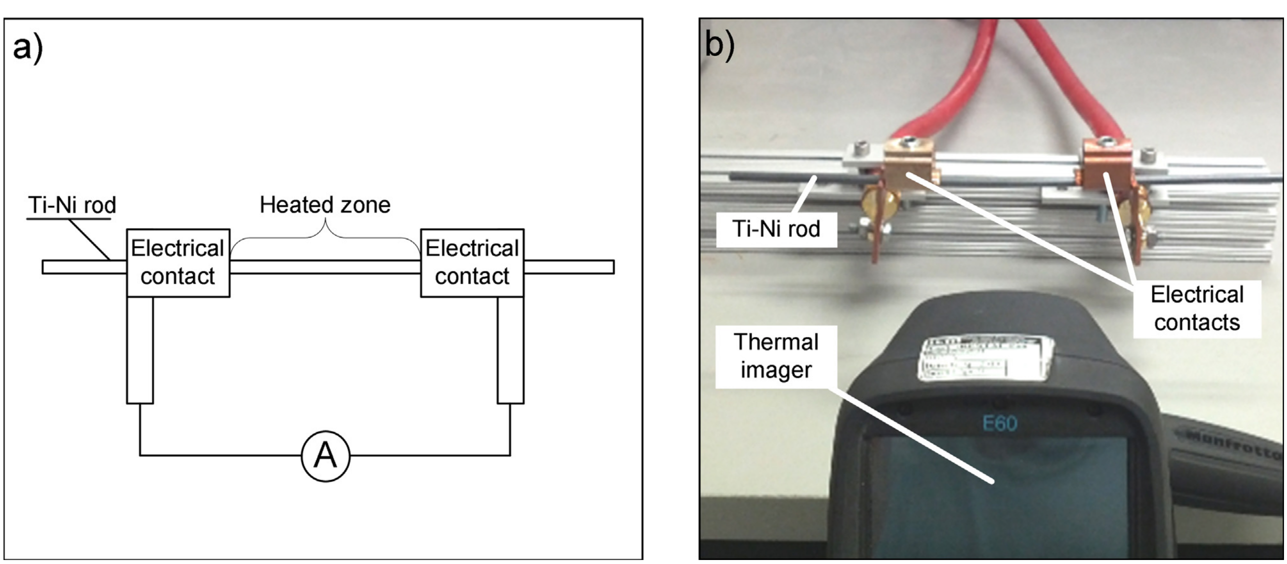

Fig. 2. Joule-heating local annealing setup: (a) schematic representation; (b) photography.