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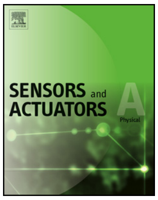

Design and fabrication of thin-walled reservoir based on microcasting assisted by vacuum for neutral argon plasma system in minimally invasive medical devices

J.A. Rodrigues*, M.F. Silva, H. Puga, J.H. Correia

CMEMS-UMinho, University of Minho, Campus Azurem, 4800-058, Guimaraes, Portugal

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ABSTRACT

This paper presents a solution to implement neutral argon plasma (NAP) in minimally invasive medical devices for therapeutic endoscopy. The NAP system is composed of compressed inert gas (argon), two electrodes, and a high-voltage source to ionise the argon. The miniaturisation of an argon reservoir is required. Finite-element method simulations of small reservoirs of an aluminium alloy with thicknesses of 0.2, 0.4, and 0.6 mm at a pressure of 7 atm were performed. The numerical results show total deformation of 108 μm, stress of 160 MPa, and a safety factor of 1.8 for the thinnest argon reservoir, resulting in a component with no permanent deformation. A small reservoir was formed via vacuum-assisted microcasting. The prototype exhibited a small and thin-walled argon reservoir.

1. Introduction

Research on minimally invasive medical devices (MIMDs) has increased in recent years. The emergence of new medical devices has improved the diagnosis and visualisation of tissues that were previously not observed in a minimally invasive manner. In endoscopy, for example, the endoscopic capsule has revolutionised the visualisation of the gastrointestinal tract, allowing painless visualisation of the entire small bowel. Endoscopic capsules have evolved from passive diagnostic devices to active mobility systems with potential therapeutic capacity [1,2]. The latest developments in mobility of autonomous MIMDs, with the possibility of stopping and rotating the MIMD, allow the integration of therapeutic techniques, such as neutral argon plasma (NAP) [3]. Fig. 1 illustrates the integration of NAP in an autonomous MIMD.

Gas discharges in argon are finding increased applications in electrosurgery, where they are used to induce mostly superficial thermal effects on tissue in a non-contact manner. Argon plasma coagulation (APC) is a monopolar electrosurgical technique used in conventional endoscopy to coagulate and ablate tissue by applying argon discharges at the atmospheric pressure [4,5]. Argon is used because it is biochemically inert, has a low breakdown voltage, and is relatively inexpensive. Argon facilitates the arc of current between the target tissue and the active electrode (stainless steel or tungsten electrode, generally a wire), creating a low-impedance zone in the air between the active electrode and the tissue. The distance between the electrode and tissue is typically 2–10 mm. An alternating voltage with a typical amplitude of 4 kV and a frequency of 350 kHz is used to ionise the flow of inert gas in a tube surrounding the electrode and to affect the tissue without contact [4].

NAP is a therapeutic technique similar to APC and bipolar electrosurgery that allows tissue coagulation via the electrically neutral flow of ionised gas [6]. This technique uses an inert gas (argon) and a voltage around 30–60 V (applied between internal bipolar electrodes) to ionise the argon and produce highenergy electrically neutral plasma. The plasma has thermal, kinetic, and light energy that allows the destruction of tumour tissue and blood at the application site. Subsequently, a small coagulum is formed, which seals the surface of the tissue [6–8]. The depth of tissue penetration ranges from 0.5 to 2 mm, depending on the application time of plasma in the tissue (1–3 s). In contrast to electrosurgery techniques, the NAP is remarkably gentle, minimising the thermal damage to the underlying and adjacent tissues. This technique uses approximately 10% of the gas flow used in the APC. The gas flow is typically <0.4 L/min, reducing the risk of air embolism and intraperitoneal overpressure [6,7].

NAP is currently used in several surgical procedures, including gynaecology, surgical oncology, plastic surgery, thoracic surgery, hepatic surgery, and general surgery [8]. This paper proposes the

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* Corresponding author.
E-mail address: id5730@alunos.uminho.pt (J.A. Rodrigues).

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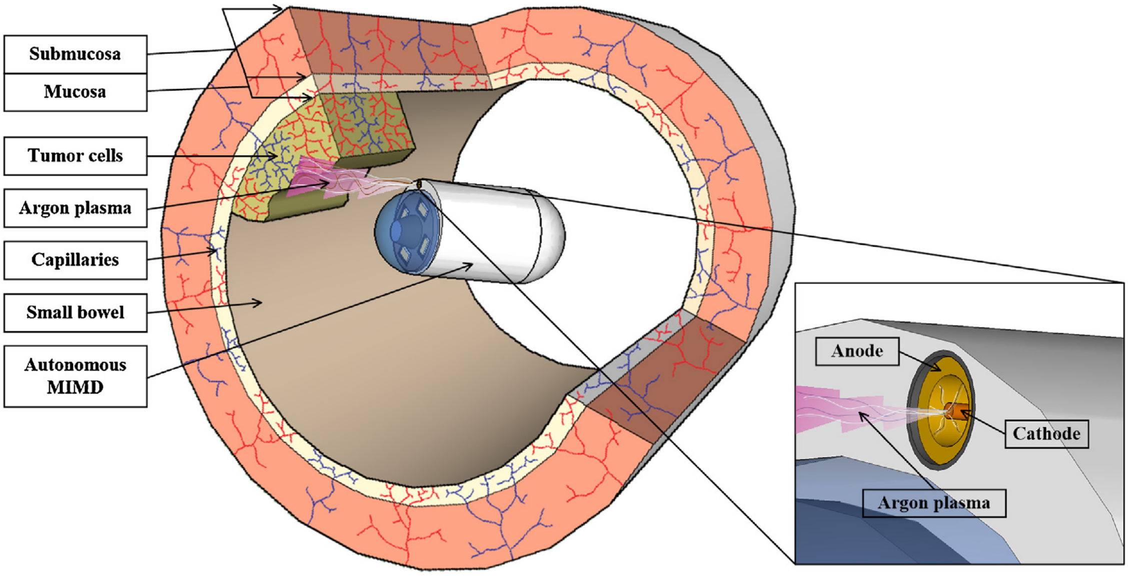

Fig. 1. NAP integrated in an autonomous MIMD for therapy in the small bowel (inaccessible to traditional endoscopic instruments).

introduction of the NAP technique for therapy in endoscopy. For this, a small argon reservoir is needed to integrate the NAP into the MIMD. With the recent advances in additive manufacturing techniques [9,10], it is possible to produce complex and thin-walled models through the investment-casting technique. Although recent studies have investigated the manufacturing of thin-walled via investment casting [11], the design in the manufacturing process and its relationship with the final structural resistance of the specimens is frequently neglected. Hence, for overcoming the difficulty of filling the mould cavity, the vacuum-assisted microcasting technique presents a promising solution that is capable of offering a combination of performance, biocompatibility, and low cost with specific details, compared with the conventional manufacturing methods [12].

Herein, the design, simulation, and fabrication of a small and thin-walled argon reservoir via vacuum-assisted microcasting in a ceramic mould are presented.

2. Computational modelling

Numerical simulations have been performed to study the structural behaviour to predict the minimal cavity thickness of the reservoir for supporting a specific pressure.

Volume is one of the three state variables of gases; the others are pressure and temperature. The ideal gas law relates the pressure, volume, and temperature to the number of moles of the gas:

$$PV = nRT, \tag{1}$$

where P is the gas pressure, V is the gas volume, n is the number of moles of the gas, R is the universal gas constant (0.08206 $L\,atm\,mol^{-1}\,K^{-1}$), and T is the absolute temperature of the gas (in Kelvin). This law states that if the volume and temperature of a fixed amount of gas do not change, the pressure also remains constant [13].

According to Boyle's law, if the temperature is kept constant, the volume of a given amount of gas is inversely proportional to the pressure; i.e. the product of the pressure and volume is a constant [13]. For comparing the same substance under two different sets of conditions, the law is expressed as

$$P_1 \cdot V_1 = P_2 \cdot V_2, \tag{2}$$

where P_1 and V_1 represent the original gas pressure and volume, respectively, and P_2 and V_2 represent the gas pressure and volume for the second condition, respectively.

The endoscopic capsule is a very small medical device, in which management of the internal space is a critical issue. To avoid compromising the dimensions of the endoscopic capsule, a small-volume argon reservoir is required. The gas flow used in the NAP technique is less than 0.4 L/min (6.67 mL/s). Assuming an argon flow of 3.3 (3) mL/s (0.2 L/min) over 1 s, the volume of argon used in the treatment is 3.3 (3) mL or 3333 mm^3 (1 atm, 37 °C). A pressure of 7 atm and temperature of 37 °C inside the argon reservoir were used for the calculations of the argon reservoir volume. At the same temperature and the same amount of matter (n), the volume of the argon reservoir is given by

$$P_1 \cdot V_1 = P_2 \cdot V_2 \Leftrightarrow 1 \times 3333 = 7 \times V_2 \Leftrightarrow V_2 = 476.1\,mm^3. \tag{3}$$

Therefore, the volume of the argon reservoir at a pressure of 7 atm for achieving an NAP flow of 0.2 L/min over 1 s is approximately 476 mm^3. Fig. 2a presents the dimensions of the argon reservoir to implement inside the MIMD. These dimensions are the results of an optimisation with thicknesses of 0.6, 0.4, and 0.2 mm. The shape of the argon reservoir matches the current MIMD for endoscopy.

A finite-element method (FEM) was used to simulate the argon reservoir deformation and perform a static analysis of the pressure and temperature. A mesh of the three-dimensional (3D) analysis type (Mechanical Physics Preference) was generated, with 2951 elements and 5898 nodes (Fig. 2b). A pressure inside the reservoir of 7 atm (709,275 Pa) and an external temperature of 37 °C (temperature inside the human body) were considered.

3. Fabrication

The microcasting technique can be considered as a precision casting process whereby wax/polylactic acid (PLA) patterns are converted into solid thin-walled metal parts following a multi-step process, as shown in Fig. 3.

The process for obtaining the ceramic mould starts with the model fabrication. The original model can be made of wax, clay, wood, plastic, or another material. In recent years, with the emergence of 3D printing, the use of the standard PLA filament to rapidly produce models has become popular. In this study, 3D models were