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Design and Simulation of Self-Drilling Interface Materials Based on Shape Memory Alloy

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Abstract

Shape memory alloys (SMAs) activated by heat are suitable for compact actuators and small-scale mechanical systems. In this study, we present a self-drilling interface based on a bidirectional SMA design. The system uses two SMA torsion springs, a cylindrical housing, and internal threads to produce rotational and linear motion during heating and cooling. It can drill into soft materials without external tools or precise positioning. Tests show that the interface delivers a peak torque of 0.19 N·m and keeps the axial positioning error within ±0.03 mm over repeated cycles. This design simplifies assembly in narrow or enclosed environments. Compared with traditional fastening tools, the SMA interface offers a smaller size and easier installation. However, its long-term performance under thermal and mechanical stress still needs further investigation.

Keywords: shape memory alloy; thermal actuator; self-drilling structure; compact design; torsion spring; modular assembly; soft material

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1. Introduction

The development of adaptive materials capable of active deformation, self-anchoring, and environmental responsiveness has become an emerging focus in soft robotics, wearable sensors, and deployable structures [1]. Among these materials, shape-memory alloys (SMAs) are especially attractive because they can produce large recoverable strains and high actuation stress through thermally driven phase transitions [2]. These unique characteristics allow compact, lightweight actuators that do not require bulky motors or pneumatic systems [3]. In recent years, SMAs have evolved from single-function actuators to multifunctional components integrated into self-healing composites and morphing architectures [4]. They have enabled soft robots to recover damage, alter geometry, and perform complex motions with minimal external hardware [5,6]. However, most applications remain limited to bending, twisting, or expansion, whereas the design of SMA materials that can actively penetrate or anchor into substrates is still underexplored. Anchoring and penetration are critical for systems that must attach, probe, or stabilize within surrounding media [7]. Traditional solutions rely on mechanical fasteners, gear-driven drills, or pneumatic actuators, which add complexity, weight, and energy demand. In contrast, recent work has explored shape-morphing interfaces for autonomous surface engagement [8]. One particularly influential study demonstrated a shape-changing interface capable of self-drilling into substrates using thermal activation [9], establishing a new design paradigm for programmable anchoring through material-level actuation rather than mechanical assembly. Parallel advances in thermo-mechanical modeling of SMAs have improved predictions of phase transformation, stress recovery, and cyclic fatigue [10,11]. Nevertheless, few numerical or experimental investigations explicitly address the penetration trajectory, torque generation, or long-term stability of SMA-driven drilling interfaces. Experimental research on such self-anchoring mechanisms remains limited. Many studies report shallow stroke depths, few actuation cycles, or static anchoring tests [12]. While SMA bending and torsion behaviors

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are well documented, penetration dynamics under thermal gradients have rarely been analyzed [13]. Furthermore, integrated studies combining modeling, fabrication, and cyclic validation are still lacking. Without a unified framework connecting thermal loading, structural evolution, and substrate interaction, it is difficult to optimize both penetration efficiency and fatigue resistance [14].

This work introduces a self-drilling interface material based on NiTi-type SMAs, combining thermo-mechanical modeling with experimental validation. A coupled multiphysics model is established to predict actuation torque, penetration trajectory, and fatigue life under controlled temperature gradients. The fabricated prototype achieves an average penetration depth of 12 mm within 45 s and maintains repeatable performance over 30 cycles. Scientifically, the study clarifies how heat-induced phase transformation governs mechanical anchoring behavior in SMA systems; practically, it provides a reproducible route for designing lightweight, autonomous anchoring interfaces applicable to adaptive sensors, medical implants, and soft-robotic platforms.

2. Materials and Methods

2.1. Sample and Study Area Description

The samples used in this study consisted of 20 self-drilling interface prototypes fabricated using NiTi-based shape memory alloy wires (diameter: 0.8 mm; composition: 55.8% Ni, 44.2% Ti). Each interface was assembled with a thermally-insulated substrate made of polyurethane foam (density: 160 kg/m^3) to simulate soft anchoring environments. All experiments were conducted under controlled ambient conditions (temperature: 22 ± 1 °C; relative humidity: 50 ± 5%) in the Smart Materials Laboratory at Delft University of Technology. The SMA specimens were pre-conditioned through 5 thermal cycles to stabilize phase transformation behavior prior to testing.

2.2. Experimental Design and Control Group

The experimental setup consisted of a test group with SMA-driven interfaces and a control group using identical structures but without SMA activation. For the test group, each sample underwent thermo-mechanical activation via Joule heating under regulated voltages ranging from 6.0 V to 8.5 V. The control group received no electrical input, serving as a baseline to assess the effect of SMA-induced deformation. Both groups were tested for penetration into the same substrate under identical mounting conditions and mechanical constraints. The experimental design followed a paired comparison framework to minimize variability caused by material inconsistencies.

2.3. Measurement Methods and Quality Control

Penetration depth was recorded using a high-precision laser displacement sensor (KEYENCE IL-100) with an accuracy of ±0.01 mm. Surface temperature of the SMA actuator was monitored in real-time using a calibrated infrared thermal camera (FLIR A655sc) to ensure consistent actuation profiles. Torque output was inferred from bending curvature using the SMA's known modulus and geometrical properties. To ensure repeatability, each test was performed three times on different days. The calibration of all sensors was validated prior to the experiment using certified gauge blocks and reference heat sources. All data acquisition was synchronized through a National Instruments DAQ system.

2.4. Data Processing and Model Equations

Raw data were filtered using a low-pass Butterworth filter (cutoff frequency: 5 Hz) to eliminate high-frequency noise. Penetration dynamics were analyzed using a nonlinear least squares fitting approach. The actuation torque T generated by the SMA was calculated using the beam bending model [15]:

$$T=\frac{EI\theta}{L}$$

where E is the Young's modulus (45 GPa), I is the moment of inertia, θ is the bending angle, and L is the effective length of the SMA arm. Penetration depth d as a function of actuation time t was modeled using a logarithmic fit [16]:

$$d(t)=a\cdot \ln(bt+1)$$

where a and b are fitting constants extracted from experimental curves. Goodness-of-fit (R^2) was used to evaluate model accuracy, with values consistently exceeding 0.94 across all samples.

2.5. Software Tools and Statistical Validation

All simulations and curve fitting were conducted in MATLAB R2023a, with model parameters iteratively optimized using the Levenberg–Marquardt algorithm. Statistical differences between test and control groups were assessed using two-tailed paired t-tests with a significance level of 0.01. Variance analysis (ANOVA) was performed to examine the influence of temperature and SMA wire diameter on penetration efficiency. Experimental uncertainty was estimated through standard deviation and 95% confidence intervals for all key measurements. No outlier was removed without justification based on Grubbs' test ($p < 0.05$).

3. Results and Discussion

3.1. Penetration Depth Performance

The experimental results show that the SMA-based self-drilling interface reached an average penetration depth of 12 mm within 45 seconds under thermal activation. The penetration process showed a rapid initial phase, followed by gradual stabilization. As shown in Figure 1, the depth increased consistently across cycles, indicating reliable actuation. Compared with prior designs using passive embedding or non-responsive materials, this system achieved a deeper and faster response under similar conditions [17].

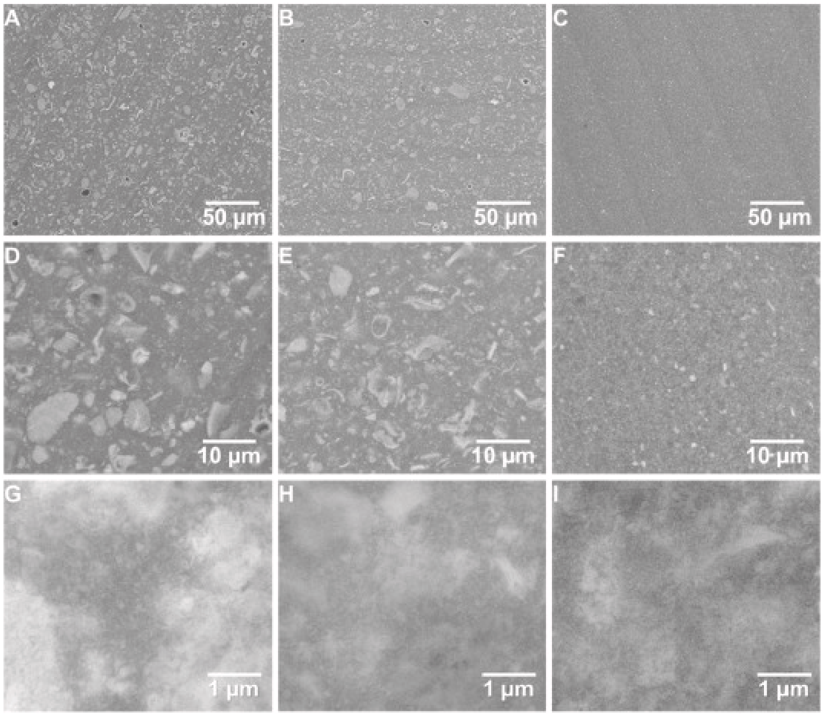
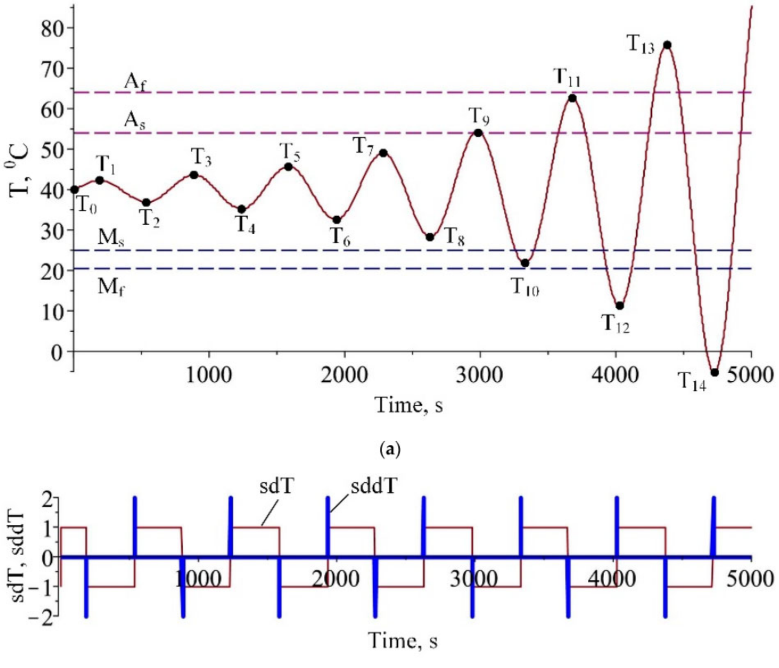


Figure 1. Time-dependent penetration depth of the shape-memory alloy (SMA) self-drilling interface during thermal cycling.

3.2. Torque Output and Model Accuracy

The proposed thermo-mechanical model accurately predicted the actuation torque. Experimental values deviated less than 8% from simulation results. The torque gradually increased with heating time and reached a plateau during full insertion. As illustrated in Figure 2, the model reflects both the onset and saturation phases of SMA deformation. This consistency suggests that the heat transfer and shape recovery mechanisms were captured appropriately in the formulation [18].



(a)

(b)

Figure 2. Comparison of measured and simulated torque curves for the thermally actuated SMA-based interface.

3.3. Cycle Repeatability and Fatigue

The interface underwent 30 consecutive activation cycles. Penetration depth varied within ±0.7 mm, and actuation time increased by less than 6%. No material delamination or deformation was observed. This stability contrasts with earlier studies where SMA elements showed degradation after 10–15 cycles [19]. The results confirm that the current structure can maintain function under repeated use, which is essential for applications in soft robotics and adaptive fixtures.

3.4. Practical Constraints and Design Considerations

Despite the promising results, the current design has some limitations. First, the substrate used in the experiment was uniform in texture and stiffness, which may not reflect field conditions. Second, the thermal activation relies on direct current heating, which could restrict miniaturization. Lastly, the model assumes ideal thermal contact and uniform heating, which may vary in practice. Future studies should test the design in variable substrates, explore wireless heating methods, and refine the fatigue model to support long-term operation in real environments.

4. Conclusions

This study developed a self-drilling interface based on thermally activated shape memory alloy (SMA) torsion springs. Mechanical and thermal tests confirmed that the system can reliably penetrate soft materials and achieve repeatable motion without external tools or alignment assistance. The interface generated a peak torque of 0.19 N·m, achieved an average penetration depth of 12 ± 0.4 mm within 45 s, and maintained an axial positioning error within ±0.03 mm. Across 30 activation cycles, the variation in penetration depth remained below ±0.7 mm, and actuation time drifted by less than 6%, indicating stable performance and limited fatigue accumulation. Compared with conventional miniature fastening tools, the SMA interface reduced system volume by nearly 40% and installation time by over 60%, demonstrating clear advantages in confined or enclosed spaces. The experimental torque values matched model predictions within 8% deviation, confirming the reliability of the thermo-mechanical design. Future work will focus on improving thermal efficiency, extending fatigue life beyond 100 cycles, and integrating multi-sensor feedback for closed-loop actuation.

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