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Characterization of a shape memory alloy interference coupling

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Abstract

A versatile and heretofore unutilized coupling is obtained by press-fitting a hollow nickel titanium shape memory alloy (SMA) shaft into a steel hub. This produces an SMA interference coupling that is distinct from other SMA actuators by the method in which the SMA is used. Press-fitting the hollow SMA shaft in its detwinned martensitic phase into a steel hub creates a joint capable of holding parts such as emergency doors, satellite solar panels, or tamper locks securely together until commanded release. Release is accomplished by heating the SMA to its activation temperature. The resulting decrease in diameter of the hollow SMA shaft allows it to easily slip out of the hub, releasing the part. Load testing of the SMA interference coupling showed ultimate strengths about twice that of traditional press-fit coupling strength calculations. The coupling can be designed to be a simple mechanism of very small size, on the order of one cubic centimeter, capable of achieving coupling strengths in excess of 4000 N (900 lbf).

Keywords: shape memory alloy, interference coupling, release mechanism

(Some figures may appear in colour only in the online journal)

1. Introduction

This research was motivated by the desire to develop a simple and reliable, zero-shock coupling device for very small satellite applications. The design solution combined the simplicity of the interference joint and the reliable mechanical actuation of shape memory alloy (SMA). The use of SMA overcame other materials' lack of a coefficient of thermal expansion large enough for reliable decoupling of the interference joint. SMA phase transition became the mechanism for transforming an interference joint into a coupling capable of holding significant load yet able to be actively commanded or passively allowed to disassemble.

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SMAs can absorb and dissipate mechanical energy wherein a shape change is induced by a change in temperature, and the temperatures that govern the SMA's response can be manipulated by adjusting the alloy's composition. The shift in atomic shear lattice structure resulting in the associated shape change is known as a phase transition [1]. SMAs exist in two phases: high temperature austenite and low temperature martensite, each with their unique material properties. The cooler martensite can be separated into two variants: twinned martensite and detwinned martensite. The detwinned form is produced by applying stress to mechanically deform the twinned martensite, forcing a shift in the alloy's microstructure. It should be noted that the stress level for reorientation of martensitic phase variants is lower than the permanent plastic yield stress of martensite as both variants of martensite are within the elastic region of nickel titanium (NiTi) SMA [2]. The detwinned SMA experiences an increased strain upon heating and subsequent phase



SMA Shaft Outer Diameter HTR & Hysteresis Cycle

Austenite to Twinned Martensite (repeatable hysteresis)
Detwinned Martensite to Austenite (HTR)
Figure 1. Unconstrained Hollow SMA Shaft Outer Diameter versus Temperature.

transition to its hotter austenitic phase or 'memory shape'; the SMA cannot return to detwinned martensite until cooled to twinned martensite and the requisite stress applied again. This one-way, constant volume transformation is known as the Heat-To-Recover (HTR) process [3] and results in a significant decrease, about four percent, in the outer diameter (OD) of the hollow SMA shaft used in this study. Figure 1 shows the diameter of the hollow SMA shaft as a function of temperature for an SMA designed to transition from its detwinned phase at ~100 °C. The one-time transition from detwinned martensite to austenite is noted by 1 and the repeatable thermal hysteresis of the SMA between austenite and twinned martensite is noted by 2. This hysteresis varies the OD only about two percent between phases and occurs at a lower temperature. Although either of these transitions could be used to affect a release of a hollow SMA shaft from a hub, this study focuses on using the larger OD change resulting from the detwinned martensite to austenite shape memory effect.

An SMA interference joint is produced by press-fitting a hollow NiTi SMA shaft, in its detwinned martensitic phase, into a steel hub. The resulting joint is unique in that the SMA shaft can subsequently decouple upon command by heating the SMA into its smaller austenitic memory shape, allowing separation of the press-fit SMA shaft and steel hub. The coupling described in this study relies on the shape memory effect decrease in the OD of a hollow SMA shaft that occurs upon heating and transition from detwinned martensite to austenite. The decrease in the shaft's OD permits the release of the shaft from the hub when pulled with a slight force, such as that exerted by a small spring. The SMA material allows for interference fits of several mils (~0.1 mm), resulting in a strong interference coupling with unique properties and application potential, discussed in detail by Crane [4] and covered by US patent(s) Crane, Oppenheimer, Romano, Newman [5, 6].

2. Implementation

Common industry interference joints are created by pressfitting a steel shaft into a hub with a particular interference, usually less than one mil (0.03 mm) [7]. The amount of pressure within an interference joint is dependent on the materials' modulus of elasticity, Poisson's ratio, and the amount of diametrical interference. Since martensitic NiTi SMA is relatively ductile as compared to materials such as steel, a larger interference can be chosen without galling the material during the press-fit process. Large interferences, such as five mils (0.13 mm) or more, between the shaft and hub can result in internal pressures in excess of 1000 MPa at a material's boundary. These internal pressures present the possibility of the detwinned martensite becoming twinned during the press-fit process, suggesting that interferences of five mils might be excessive for this application as discussed later in this paper.

Characterization of the SMA interference joint for use as a coupling began with precision measurements of a hollow NiTi SMA shaft during unconstrained hysteresis cycling, as shown in figure 1. The SMA, Ti 45%; Ni 55% by weight, is formed using a proprietary process by the manufacturer, Intrinsic Devices, Inc. Next were measurements of the axial coupling strength of four assembled SMA interference joints by applied loading on a tensile test machine to validate the SMA interference joint coupling concept, as shown in figure 2. The SMA shafts had a nominal outer diameter of 0.312 inches (0.792 cm) and the hubs had a nominal inner diameter of 0.311 inches (0.790 cm). Finally, an engineering design unit coupling device using the SMA interference joint



Figure 2. Force vs. Displacement for Different Interference Fits of an SMA Shaft Press-fit into a Steel Hub (SMA Interference Coupling Concept Validation Test).



Figure 3. Creation of an SMA Interference Coupling from Press-fit to Commanded Disassembly.

was built and tested in the laboratory as a zero-shock, nonexplosive actuator (NEA) to show that the coupler would release upon command [4].

At two mils (0.05 mm) of interference and less, figure 2 shows the expected linear drop off of coupling force versus displacement after static friction transitions to kinetic friction. However, at three mils (0.08 mm) of interference, the SMA interference joint strengthened significantly beyond what traditional press-fit strength equations predicted [4]. A stair-stepping increase in axial coupling force is observed in figure 2, during forced extraction of specimen #4; with a peak force almost twice that of the initial static friction peak. The disparity in specimen coupling strengths during this initial test led to a continued characterization of the unique interactions between the SMA shaft and steel hub during forced decoupling.

3. Design, testing, and results

Typically, NiTi SMA rings are valued for their clamping capability and remain in their austenitic or memory shape after activation [3]. By contrast, use of SMA as the shaft for an interference joint relies on the non-memory detwinned martensite material strength to hold its OD shape. SMA's ductile martensitic phase, as explored in the medical field for wear durability [8], is useful in creation of the SMA interference coupling described here. Figure 3(a) shows the process used in this study for press-fitting a hollow NiTi SMA shaft in its detwinned martensitic phase into a steel bushing to create the interference joint. High temperatures were not used to induce thermal expansion of the steel hub during the pressfit process; as is common in industry shrink-fit processes [7]. If the hub were heated, it would likely initiate a complete SMA HTR phase transition during the press-fit and prematurely cause the diameter reduction intended for later use to decouple the hollow shaft from the hub. Of course, it is important for the SMA shaft to come cleanly out of the steel hub during decoupling. Therefore, the design was such that once the SMA shrinks to its austenite form through HTR and eventually slightly enlarges again upon cooling to twinned martensite; the SMA shaft OD should not be large enough to reengage the steel hub even if the SMA shaft has not been fully extracted from the hub.



Figure 4. Typical Test Data from a Forced Decoupling of an SMA Interference Joint.

The NiTi SMA press-fit is done at room temperature while in its more ductile martensitic phase. Press-fitting the hollow SMA shaft in this state allows the mechanical energy stored in the detwinned martensitic atomic structure to strengthen the interference coupling by increasing the normal forces of the shaft against the hub. In addition, NiTi alloy has an inherently higher coefficient of friction in its martensitic phase than in its austenitic phase [8]. The increased normal force and the higher coefficient of friction translate to a stronger SMA interference coupling.

Assembly of the coupling is shown in figure 3(b). The coupling is created by the head of the retaining bolt pressing against the hollow shaft, and the threaded end of the retaining bolt attached to whatever is being restrained. Commanded release of the SMA interference coupling is accomplished by applying heat to the steel hub. Conductive heating of the SMA through the steel hub enables the phase transition of the SMA from its larger diameter martensitic phase, into its smaller diameter austenitic phase or memory shape. Once heated, the SMA shaft and the retaining bolt slide out of the steel hub. Details of the construction and test of a NEA engineering design unit are elaborated in [4].

Strength testing of the SMA interference joint was performed using a test rig that would subject the coupling to high axial loads. The test rig, constructed of 1¹/4" (3.18 cm) diameter, type 304, stainless steel, properly aligned the SMA interference coupling into a tensile test machine [4]. The test rig top and bottom were joined using the coupling's retaining bolt that catches the hollow SMA shaft and then inserted into the tensile machine. Load cells recorded the force used to separate the SMA shaft from the casehardened steel hub during the tensile test.

Three lots of ten test specimens each were created with interference fits of approximately one, three, and five mils (0.03, 0.05, 0.08 mm, respectively). These specimens had shafts with a nominal outer diameter of about 0.200 inches (0.508 cm) and a hub with nominal inner diameter of 0.199 inches (0.505 cm), with complete testing details found in [4]. A stair-stepping increase in axial coupling force characterized as frictional transitions were again observed after the initial loading static friction peak, resulting in an increased resistance to extraction and a much higher ultimate strength of the SMA interference coupling, as shown for a typical test specimen in figure 4. Finally, after about half of the shaft was removed from the hub, a smooth roll off in extraction force was recorded as the coupling's internal surface contact area continued to decrease and the SMA separated from the steel hub. It should be noted that SMA interference joints were created in both top-down and bottom-up press-fit directions that either matched or opposed the forced extraction direction. No correlation between joint strength and press-fit direction was observed. Initial static friction peak strengths of 140 to 457 lbf (620 to 2030 N) and ultimate strengths of 325 to 916 lbf (1450 to 4070 N) were achieved for a nominal extraction speed of one mm/minute for the different interference values. Maximum recorded extraction forces, corresponding to maximum coupling strengths, were achieved with the three mil (0.08 mm) nominal interference test lot, shown by dashed trend lines in figure 5. The SMA and hub surfaces were inspected after the tests and representative photos are discussed by Crane [4], revealing a scratching along the extraction axis and a polishing of some of the contact surfaces, increasing with interference.



Figure 5. Coupling Strength Test Data with Predicted Strength Values (SMA Interference Coupling Lot Test).

4. Analysis

As discussed in [4], traditional press-fit equations, usually used for relatively small interferences, were used to predict the SMA interference joint's strength. These equations predict a linear increase in frictional axial holding force as a function of interference (shown as 'x's along the predicted strength least squares line in figure 5). The predicted interference-fit, coupling-strength data were based on a coefficient of friction $(\mu_{\rm f})$ of 0.13, estimated after studying [9]. The good agreement between the predicted trend line and the measured static friction peaks at interferences of one and three mils (0.05 and 0.08 mm), suggests that the actual (experimental) value of the coefficient of static friction is indeed about 0.13, as estimated. The average initial static friction peak strength was predicted reasonably well for the one and three mils (0.08 mm) interference couplings, however, the average initial static friction peak at five mils (0.13 mm) interference was significantly less than the press-fit equations result. The cause of this deviation from predicted strength is likely due to excessive interference between the hollow SMA shaft and steel hub. Too much interference could begin a reverse straining process: a compressive force similar but in the opposite direction of the expansive force needed to originally create the larger outerdiameter, detwinned-martensite state of the SMA shaft. Reversion to twinned martensite of part of the shaft would presumably reduce the hoop stress and, therefore, reduce the force needed for extraction, possibly explaining the lack of increase in the extraction force when the interference increases from three to five mils, as seen in figure 5.

Clearly press-fit SMA interference joints are different from traditional interference joints due to the unique properties of NiTi alloy, and traditional press-fit equations do not adequately predict the ultimate coupling force results. An interference joint's surface condition and geometric accuracy of its joined hub and shaft are the two most important factors contributing to the value of μ_f [9]. As discovered in Chatterjee's SMA high friction testing [10], μ_f of NiTi SMA in its martensitic form increases as applied loading increases. This is contrary to traditional press-fits using non-shape memory materials where the coefficient of static friction is constant with relation to the interference pressure. Since the highest radial pressures or hoop stressors, which translate to normal forces within the interference joint, are found at the boundary of the shaft/hub interface, and the SMA's non-linear $\mu_{\rm f}$ indicates that mechanical friction rather than adhesive friction may dominate without inducing plastic deformation in the SMA [10], it is hypothesized that an increasing μ_f is a causal factor producing the ultimate strength coupling forces that were not predicted. It is also hypothesized that the imperfect geometry of the hollow SMA shaft and steel hub could induce martensitic variants from pressure point 'hot spots' as pressures internal to the SMA interference joint were >400 MPa for the test interferences; therefore, within martensitic transformation pressures [1]. This would be important during the interference joint's assembly and forced extraction as the coupling's creation and design intentionally places the SMA shaft in compression, perhaps inducing buckling modes of the SMA in the same manner as a column under excess loading. Although it is not exactly clear how, these internal changes of the SMA shaft geometry within the interference joint must be

increasing normal forces and subsequently the ultimate strength of the SMA coupling.

In contrast to the good agreement between the static friction peaks and the predicted trend line for the one and three mil test lots, the increase in ultimate strength coupling force was unexpected and occurred differently for the two tests represented in figures 2 and 5: not occurring until the three mil interference for the first SMA interference-coupling, concept-validation test shown in figure 2, but occurring for even the one mil interference for the interference coupling lot test shown in figure 5. This is most likely due to the differing shaft/hub dimensions between the two tests, but a common result to both tests was that applied extraction force had to be increased even though less and less of the SMA shaft was in contact with the hub during extraction. It was not until after about half of the shaft was out of the hub that the extraction force finally started decreasing. It may even be possible that the SMA experiences transitions back and forth between detwinned and twinned martensitic variants during the extraction process, creating the non-linear frictional transitions and increase in coupling strength beyond the predicted initial static friction peak strength. While it is possible to speculate on the reasons for these test results, more work is required to fully understand them. In any event, the increase in extraction force required to cause SMA interference coupling failure means that the SMA interference coupling is that much more secure under load.

5. Conclusion

The SMA interference coupling shows promise as a new type of zero-shock NEA. This concept permits development of mechanisms that are secure even when exposed to heavy loading, yet reliably actuate upon command to deploy or release connected parts of a device or machine. The coupling's design of very few parts and simple, single-motion actuation should minimize the number of failure modes, subject to verification by testing. An example micro-coupling device based upon the SMA interference coupling concept was successfully designed and tested as described in detail by Crane [4]. The design characteristics of small mass and single-motion actuation of the SMA interference coupling should allow for a wide range of latch and fastener applications. Alternatively, the scale of the SMA interference coupling need not be limited to small sizes, but could be scaled up in size and strength to meet other types of coupling needs. Featuring simplicity, strength, and reliability, the SMA interference coupling could be useful for many applications in systems such as safety devices, tamper locks, robotics, aeronautics, military, and spacecraft systems.

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