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Investigation of the Self-Healing Behavior of Sn–Bi Metal Matrix Composite Reinforced with NiTi Shape Memory Alloy Strips Under Flexural Loading

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Abstract

Utilizing intelligent materials such as shape memory alloys as reinforcement in metal matrix composites is a novel method to mimic self-healing behavior. In this study, the bending behavior of a self-healing metal matrix composite made from Sn-13 wt.% Bi alloy as matrix and NiTi shape memory alloy (SMA) strips as reinforcement is investigated. Specimens were fabricated in different reinforcement vol.% (0.78, 1.55, 2.33) and in various pre-strains (0, 2, 6%), and were healed at three healing temperatures (170, 180, 190 ℃). Results showed that shape recovery was accomplished in all the specimens, but not all of them were able to withstand second loading after healing. Only specimens with 2.33 vol.% of SMA strips, 1.55 vol.% of SMA, and 6% pre-strain could endure bending force after healing, and they gained 35.31–51.83% of bending force self-healing efficiency.

Keywords: Metal matrix composite, Self-healing, Bending, Shape memory alloy, Tin-Bismuth, Nickel-Titanium

1- Introduction

Over the past few decades, using inspiration from nature, researchers have focused on creating manmade materials that have the ability to self-heal defects in different materials [1]. With regard to polymeric materials, embedding liquid healing agents in microcapsules and hollow fibers [2] is known to be the most successful method for fabricating self-healing polymer matrix composites.

These methods inspired scholars to fabricate self-healing metal matrix composites. In metal matrix composites, the healing agent, which was embedded in hollow fibers and microcapsules within the matrix, was a low melting point solder alloy that filled the voids and cracks by capillarity force due to the application of temperature and melting of solder alloy [3-6].

Another method, introduced by Manuel & Olson [7], involved using 1 vol.% of NiTi shape memory alloy wire as reinforcement within an off-eutectic matrix alloy. In this method, the specimens were tensile-tested until the matrix was fully raptured, but the crack was bridged by unbroken shape memory alloy (SMA) wires. After first tensile test, raptured specimens were placed in a vacuum furnace and heat-treated for 24 hours at a temperature that activated the shape memory effect of SMA wires and also the matrix alloy experiences partial melting in a two-phase region of matrix alloy's phase diagram. The partial melting of the matrix generated the required liquid healing agent, and the

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activation of SMA wires produced the essential pressure to close and clamp the crack, improving atomic diffusion [8]. Fisher also used the same method to fabricate self-healing Al-Si MMC specimens [9, 10].

Misra [11] fabricated Sn-based self-healing metal matrix composite bending specimens reinforced by NiTi SMA wires with different matrix compositions. Rohatgi [12] used an Al-based alloy as matrix material and SMA wires as reinforcement. Ferguson [13] investigated the healing ability of Zinc alloy ZA-8 as matrix of the composite.

Using the 3D model of a self-healing metal matrix pre-cracked bending test specimen with SMA wires, Zhu [14] showed that using pre-strained SMA wires can lead to increasing self-healing efficiency due to the increase in compressive force induced by wires.

Previous studies about self-healing efficiency of metal matrix composites did not include a comprehensive experimental study of specimens' self-healing efficiency with different levels of reinforcement, pre-strain, and healing temperature. Since these parameters are the main elements that influence specimens' self-healing behavior, the need for this investigation was sensible. In this investigation, Sn-13 wt.% Bi metal matrix bending specimens were fabricated with NiTi SMA strips as reinforcement. Three different levels of each of the mentioned parameters were used for the fabrication and healing of specimens. After an initial bending test and failure of specimens, they were heat-treated in an argon atmosphere furnace. A second bending test was performed in order to calculate self-healing efficiency and to study the influence of each parameter on the healing ability of the specimens.

2- Experimental procedure

2-1- Materials

In order to fabricate Sn-13 wt.% Bi matrix alloy, commercially pure tin and bismuth (99.8%) were melted in a furnace at 300 ℃. Nickel–titanium SMA strips were used as reinforcement in different volume fractions. These strips had a rectangular cross section (0.762 mm × 0.254 mm), which made it easier to achieve higher volume fractions with the lowest number of wires. NiTi SMA strips with a composition of 45.5 wt.% Ti and 54.5 wt.% Ni were produced by Confluent Medical Technologies. The austenitic transformation temperature of wires was 110 ℃ and had a recoverable shape memory strain of about 8%. Using rectangular cross-section reinforcement with larger aspect ratios (length per width proportion) created higher interface surfaces than round wires in the same volume fraction. Since the interface is the only connection between the matrix and the reinforcement, it is the main part of accurate force transfer among the matrix and strips.

2-2- Fabrication process

There are several methods to fabricate a metal matrix composite such as powder metallurgy, casting, and liquid infiltration [15]. In this study, casting has been chosen as a fabrication method because of the available equipment and capability of controlling fabrication process more easily. To fix reinforcement in the exact accurate position during casting, a metallic mold was designed and manufactured with the ability to position continuous reinforcement uniaxially and in their specific spot by embedding internal fixtures inside the mold.

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To fabricate bending specimens, elements such as tin and bismuth, with the right mass fractions to produce an alloy with 87 wt.% tin and 13 wt.% bismuth, were melted in a stainless steel crucible at 300 ℃ and then poured into the mold.

The first step towards preparing SMA strips is removing the SMA strips' stable titanium oxide, because this layer of oxide significantly reduces the wettability of the strips' surface, thus weakening the interface strength [11]. Using an aquatic acid solution is an efficient method to etch reinforcement and remove the oxide layer [16, 17]. SMA strips were drowned into an aquatic acid solution with 4.8% of hydrofluoric acid and 10.5% nitric acid for five minutes.

2-3- Test method

Test specimens were fabricated according to the ASTM-E290 [18] standard for bend-testing metallic materials. Mechanical tests were performed using the Hounsfield H25KS universal test machine, at the rate of 1 mm/min, to ensure the repeatability of the results. A Sairan IMI 420 optical microscope was used for taking optical micrographs of the specimens' cross sections.

The self-healing efficiency of a specific property such as bending force, F (η_F), can be computed from Equation 1, in which the "ah" and "bh" subscripts mean the amount of property after healing and before healing, respectively.

$$\eta_F = F_{ah}/F_{bh} \times 100 \tag{1}$$

Three level of SMA strip's vol.% (0.78, 1.55 and 2.33) for 1 to 3 strips, pre-strain of reinforcement (0, 2 and 6 percent) and healing temperature (170, 180 and 190 ℃) were considered to be the most effective parameters on self-healing efficiency, a combination of these levels based on an orthogonal taguchi array was adopted to fabricate specimens as shown in table I.

Table I. Tested specimens with different amounts of effective parameters of healing efficiency based on L-9 taguchi orthogonal array

Specimen No.	SMA quantity (vol.%)	Pre-strain (%)	Healing temperature (℃)
1	0.78	0	170
2	0.78	2	180
3	0.78	6	190
4	1.55	0	180
5	1.55	2	190
6	1.55	6	170
7	2.33	0	190
8	2.33	2	170
9	2.33	6	180

3- Results and discussion

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Bending test results, including force displacement curves for each specimen (before and after healing), were drawn in the same diagram, and self-healing efficiency was calculated for the highest bending force of each specimen. Figure 1 shows an optical microscopic picture of the effect of using etch solution on the consolidation of matrix-strip bonding.

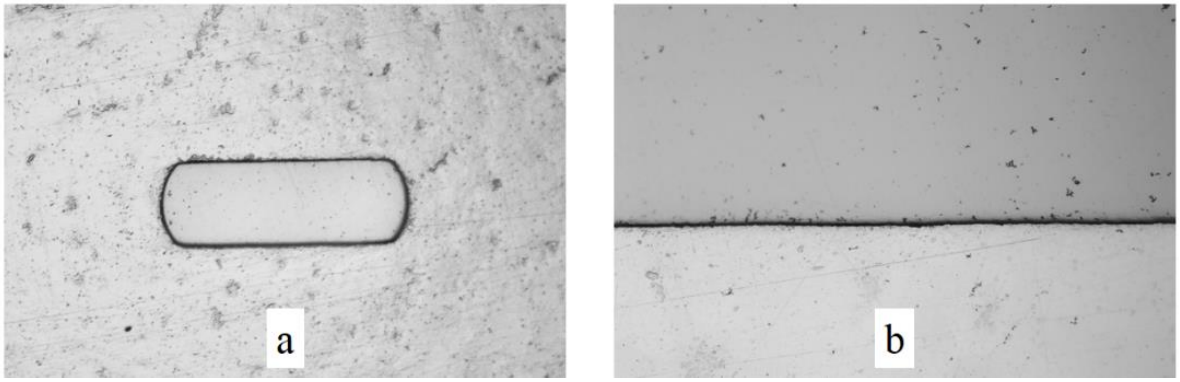

Figure 1. Optical micrograph of the cross-section interface between Sn–Bi matrix and SMA strips, a) 5x magnification, b) 20x magnification.

Of the nine specimens, Specimens 7–9, which had 2.33 vol.% of SMA, as well as Specimen 6, which had 1.55 SMA vol.% and 6% pre-strain, endured another loading after the healing process. Hence, their self-healing efficiency was calculated from Equation 1. Specimens 1 to 5 could not resist against loading after healing, so self-healing efficiency of these specimens were considered to be zero. Figure 2 shows the force-displacement diagram of Specimen 9, as an example of pre- and post-healing behavior in healed specimens. According to this diagram, the specimen experienced an initial linear elastic region, which was limited to approximately 250 N bending yield force. Thereafter, with the development of a plastic area in the cross section, the specimen underwent a plastic deformation until failure.

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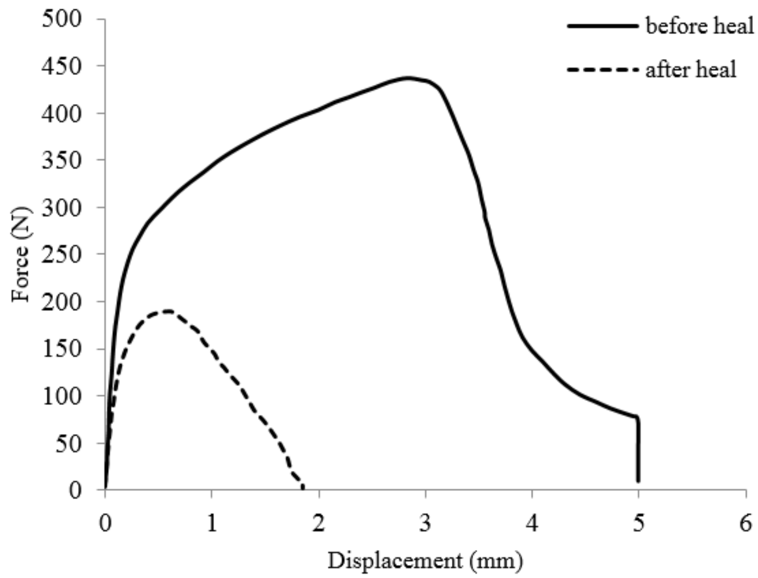

Figure 2. Force displacement diagram of Specimen 9.

Specimens 1–5 experienced shape recovery due to the activation of the strip's shape memory effect while the matrix had been softened in a two-phase region. But since large deformations took place during the initial bending test, a crack mouth opened and SMA reinforcement could not apply enough pressure force to compensate for this aperture and close the crack. The specimen's inability to heal the crack and achieve partial closure in this method of fabricating self-healing metal matrix composites was reported in similar studies in the past. Rohatgi [12], using Al-A380 alloy as matrix, observed that, although the gap between crack surfaces was reduced, due to the lack of rebonding among them, no strength recovery was accomplished. Manuel [8] also reported the partial closure of cracks in specimens with Mg-based matrix and a lack of healing. The creation of an oxide layer on the surface of the crack that prevents effective bonding between fractured parts was reported as a probable cause.

In Specimens 7–9, vol.% of SMA strips was high enough to apply required compressive force for crack closure. Specimen 6 had the highest pre-strain with two strips in the cross section. Hence, in 1.55 vol.% of reinforcement, the amount of the strip's pre-strain is the most determinative parameter. Figure 3 shows Specimen 9 after fabrication, before healing, and after healing.

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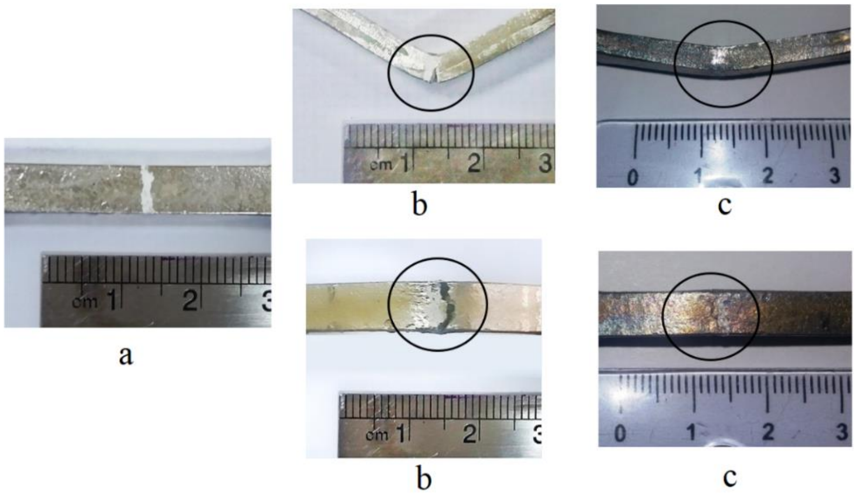

Figure 3. Specimen 9 during mechanical testing and the healing process: (a) after fabrication and before initial test, (b) after initial test and before healing, (c) after healing.

Table II presents the highest bending force endured by each specimen before and after healing, and the corresponding self-healing efficiency. According to Table II, Specimen 9 achieved the highest bending force self-healing efficiency with 51.8%, and Specimen 6 showed the lowest bending force self-healing efficiency with 35.3%.

Table II. Maximum bending forces and corresponding self-healing efficiency.

Specimen No.	Maximum bending force before healing (N)	Maximum bending force after healing (N)	Self-healing efficiency (%)
1	340.0	0.0	0.0
2	385.0	0.0	0.0
3	386.8	0.0	0.0
4	332.3	0.0	0.0
5	301.4	0.0	0.0
6	405.4	143.1	35.3
7	318.7	165.2	51.8
8	447.0	166.6	37.1
9	437.4	189.0	43.2

Specimens with 2.33 SMA vol.% achieved the highest average of bending force by enduring 400.6 N during the test. Moreover, increasing SMA pre-strain, from 0 to 2 and then to 6, increased the average of maximum bending force endured by specimens from 330.3 N to 377.8 N and then to 409.8 N. After healing, Specimen 9 showed the highest bending force by withstanding 189 N and Specimen 6 experienced 143.1 N bending force, which was the lowest amount of sustained bending force between healed specimens.

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Among healed specimens, the effect of healing temperature was noticeable. Specimens 6 and 8, which were healed at 170 ℃, had shown the lowest self-healing efficiency, 35.3% and 37.1%, respectively. Specimen 9, which was healed at 180 ℃, recorded 43.2% of self-healing efficiency, and Specimen 7, healed at 190 ℃, achieved 51.8% self-healing efficiency. This incremental increase in the self-healing efficiency with increasing healing temperature indicates that, by raising healing temperature, the melted fraction of the matrix alloy in the two-phase region would increase, meaning that there is more liquid healing agent for the healing process. However, it must be noted that increasing the healing temperature too much could lead to instability in preserving structural integrity, unwanted deformations, and harmful shape changes. This issue was pointed out by Ferguson [13]. Using zinc ZA-8 alloy as matrix, he stated that encasing specimens in a sand cast was necessary to maintain structural stability at high healing temperatures.

Although Specimens 1–5 could not be healed effectively, the SMA strips were able to significantly restore the original shape of each specimen. The average angle between the fractured parts in Specimens 1–5 was measured by a protractor as 132° , and this average angle was reduced to 162° after healing.

4- Conclusion

The following main conclusions can be drawn from this study:

- Only specimens with a very high amount of SMA volume fraction were healed, and specimens with a low volume fraction of SMA reinforcement could not heal due to lack of enough compressive force.
- Results showed that, among the healed specimens, an increase in the healing temperature increased self-healing efficiency in a perfectly linear trend.
- The highest amount of self-healing efficiency was found in a specimen that was healed at 190 ℃ with 2.33 vol.% of SMA and zero pre-strain, showing 51.8% self-healing efficiency.
- Although five specimens, with a low amount of SMA strip vol.%, could not be healed completely, an average shape recovery of 30° was observed in the angle between the fractured parts of the specimen.
- Since the volume fraction of SMA reinforcement is the main effective parameter, future studies could investigate higher volume fractions of reinforcement.

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