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Gravity and Semisolid Casting of Self-Healing Aluminum Matrix Composites

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ABSTRACT

This paper focuses on casting self-healing metal matrix composites with an aluminum alloy as a matrix, and nitinol fiber as reinforcement. The shape memory effect of nitinol fibers can cause them to shrink and narrow or close the crack in cast matrix material and in the case of a bend test, restore the shape. Self-healing metal matrix composite samples were cast using (a) semi solid squeeze casting after Rapid Slurry Formation (RSF) and (b) gravity die casting. Casting procedures, microstructures, and mechanical properties are reported. The cast aluminum-nitinol fiber composite samples prepared by both techniques were cracked under tensile and bending, both types of samples exhibit a reduction in the width of the crack in the samples upon heating the sample above the transformation temperature of nitinol. Under certain conditions, the cracks in permanent mold cast alloys reinforced with nitinol have been completely sealed leading to self-healing.

Keywords: gravity casting, semisolid casting, self-healing, aluminum, crack closure, shape memory alloy fibers, SMA

INTRODUCTION

Biomimetics involves harnessing the biological mechanisms found in various species and applying them to man-made materials. Nature and various biological organisms exhibit a unique capability of self-healing including autonomous healing of broken bone and autonomous wound recovery.[1,2] These mechanisms need to be mimicked in man-made materials for applications in automotive and aerospace applications including electronic devices.[3,4] The concept of self-healing in manmade materials is relatively recent and expansive domain of research in engineering.

Fundamentally, three key attributes are universally sought after for all materials:

- Functionality;
- Durability; and
- Longevity.[5-7]

A biologically-inspired smart structure designed to autonomously recover from damage not only ensures the long-term integrity but also leads to a significant reduction in costs related to replacement and maintenance.[8] One of the ways to synthesize a self-healing composites structure is to incorporate shape memory alloy (SMA) fibers as a reinforcement in the matrix.[9,10] The SMA fibers stretch under tensile or bending load, leading the matrix to develop cracks. The SMA fiber shrinks upon heating and applies force to the matrix. The nitinol SMA wire shrinks upon heating above 194-230F (90-110C) due to the transformation from the twinned martensite to the austenite phase.

In this process, the crack width is reduced, or the crack is completely closed. This occurrence is due to the shape memory fibers that when contracted, enable the rejoining of the crack surfaces, a process facilitated especially in the presence of a partially molten matrix.[11] This results in the effective closure of the damaged crack partially restoring the integrity of the material as shown in Figure 1. When the samples are subjected to bending to crack the matrix they recover their straight shape due to the shrinkage of the SMA wires upon heating, exhibiting shape recovery.

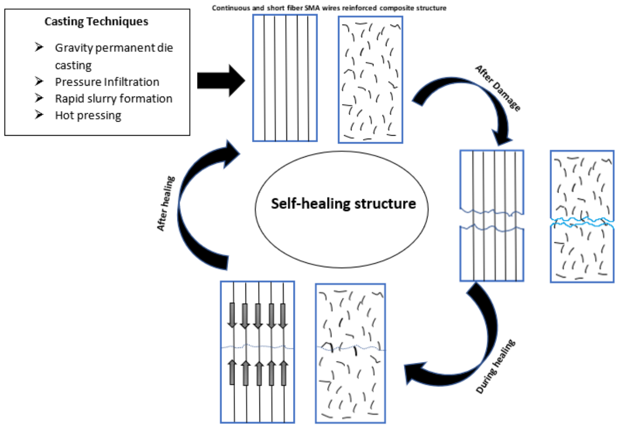


Figure 1. A pictorial concept of a self-healing metallic composite structure.

Manuel[12] at Northwestern University synthesized SMA-reinforced self-healing metal matrix composites using Sn-13at.%Bi and Mg-5.7at.%Zn-2.7at.%Al as base materials and incorporating 1 vol % of uniaxially oriented, continuous nitinol SMA wires for reinforcement. To enhance the interfacial bonding between the matrix and the fibers, the nitinol wires were etched and sputter-coated with a thin layer of gold measuring 5 nm. For Sn-13at.%Bi-nitinol, the matrix was cracked during tensile testing but the fibers remained intact. During subsequent heating, the crack formed in the Sn-13at.%Bi matrix during tensile testing was closed due to shrinkage of nitinol wires and sealed due to partial liquefaction of the Sn-13at.%Bi alloy matrix in the crack and the healed specimen demonstrated a recovery of more than 94% of its original tensile strength. For Mg-5.7at.%Zn-2.7at.%Al-nitinol, the composite showed partial crack closure after healing. SMA wires were able to close the crack, but the rough crack walls prevented full crack closure. The small fraction of SMA reinforcement wires could not provide the force to overcome the matrix strength of the Mg-based alloy.

In 2013, Wright et al.[13] introduced Shape Memory Alloy Self-Healing (SMASH) technology, using nitinol wire with different series of aluminum alloys as a matrix (i.e. Al-Si, Al-Cu, Al-Si-Cu). Effective healing was observed in Al-Si alloy, retaining 90% of its ultimate tensile strength after heat treatment. However, Al-Cu and Al-Cu-Si alloys did not show healing, attributed to their insufficient ductility preventing the SMA wire from phase transformation and crack clamping during healing. In 2015, Ferguson and Rohatgi and coworkers[14] worked on a ZA-8 Zinc alloy reinforced with nitinol wire, using both direct and indirect loading techniques for load transfer. In the direct load transfer technique, only nitinol wires were present in the sample.

In contrast, the indirect method incorporated steel rods within the sample to transfer the load caused by the shrinking of the thermally-activated nitinol wires to the matrix. Heating the samples after cracking them closed the crack completely, but only 30% of the original tensile strength was restored. Higher volume fractions of SMA wire improved the ultimate tensile strength for undamaged samples. Indirect load transfer proved more effective in achieving both full crack closure and regaining ultimate tensile strength. A 2013 study was conducted by Misra[15] at the University of Wisconsin-Milwaukee to assess self-healing properties in various compositions of Bi-Sn matrix containing a 20% volume fraction of nitinol wires, made using a pressure infiltration casting process.

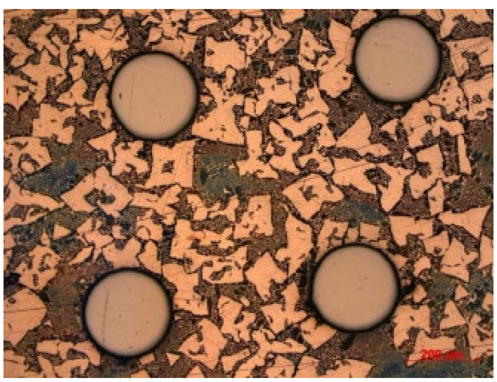
The samples, when subjected to a bending load, were bent and cracked. However, upon heating, they not only recovered their original shape but the cracks also healed. The Bi-10%Sn- nitinol has a 23% liquid content due to partial melting from heating to the healing temperature, contributing to the complete sealing of the crack at a healing temperature of 293F (145C). Furthermore, the Sn-20%Bi-nitinol exhibited a 98.9% recovery in shape (the bent sample became almost straight) and regained approximately 92% of its flexural strength after a 60-minute heat treatment at 329F (165C).

Figure 2 provides a comprehensive visual analysis of a Sn-Bi alloy and nitinol fiber composite synthesized by Misra. Figure 2(a) shows the nitinol fibers in a container where they were pressure infiltrated with Bi-Sn melt. Figure 2(b) shows the pressure-infiltrated composite. Figure 2(c) represents an optical image of the microstructure containing nitinol fibers in Sn-Bi alloy matrix. Figure 2(d) shows the straightening of the bend tested Bi-Sn composites specimen along with the crack closure with applied heat.

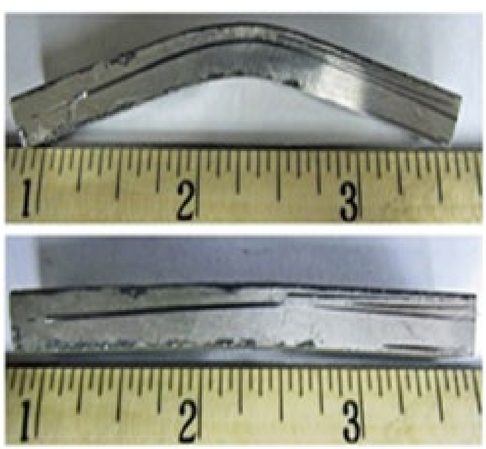
This paper describes the casting techniques which have been used to synthesize self-healing aluminum alloy composites. In three sets of experiments along with their results, it describes the matrix material, casting methodology, incorporation of the nitinol fibers in the cast matrix, microstructures, cracking of sample and self-healing behavior. The paper includes permanent mold casting and semi solid squeeze casting of nitinol fibers reinforced aluminum alloys 356, 380 and 2014, cracking the sample under tensile and bending stresses, and then heating to narrow down or close the crack. Healing implies partial or full closing of a crack in the casting and recovery of shape after healing. In this paper, in some cases, the bent shape of castings recovered to their original straight shape as a result of self-healing upon heating.

(a)

(b)



(c)



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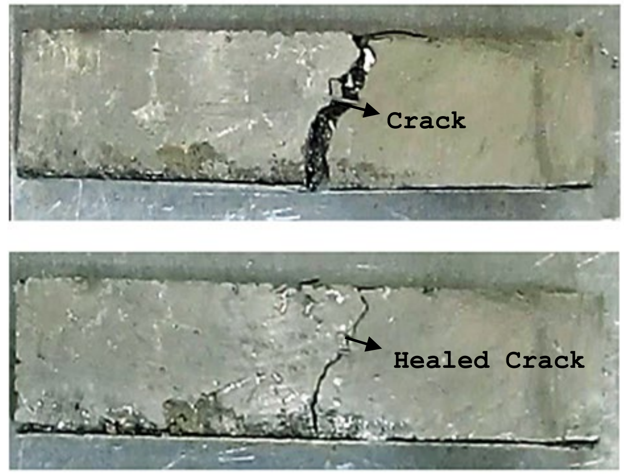


(d)

Figure 2. (a) A pictorial representation of a permanent die with the nitinol wires placed randomly in the die; (b) The cast Sn-Bi alloy-based composite structure; (c) Optical microscopy of the cross-section of the cast Bi-10% Sn-nitinol (d=500µm) sample, showing good bonding of nitinol wires with the matrix; (d) Recovery in shape for the sample under bend loading and crack closure of sample after thermal treatment.[15]

CASTING OF SELF-HEALING COMPOSITES

USING SEMI SOLID CASTING TECHNIQUE

Aluminum Alloy A356 Reinforced Nitinol Fibers Metal Matrix Composites

The work describes the casting of self-healing metal matrix composite utilizing a Rapid Slurry Formation (RSF) technique, to form a semi solid slurry and then squeeze casting the semi solid slurry in a bed of randomly arranged nitinol fibers.[16,17] The composite is composed of an A356 alloy acting as the matrix material, with random distributed nitinol wire of diameter 0.50 mm serving as the reinforcing element. The manufacturing process is divided into two separate stages. The procedure commenced by cutting nitinol wire into uniform lengths of 2.5 cm using scissors, followed by the surface treatment of the nitinol wires. Once the surface treatment of nitinol wire was done, the next step involved preparing a semisolid slurry of the A356 alloy.

Surface treatment of nitinol wires helps to have proper wetting with A356 alloy matrix. Surface treatment was done using a solution composed of 5% HF and 10% HNO_3 for a duration of 2.5 minutes. Following this, the wires pickled in H_3PO_4 to remove surface rust and further enhance surface roughness. The pickled nitinol wires were rinsed with clean water and subsequently dried using a hot air bath. Figure 3 shows the schematic flow diagram of the entire process for producing the self-healing metal matrix composites.

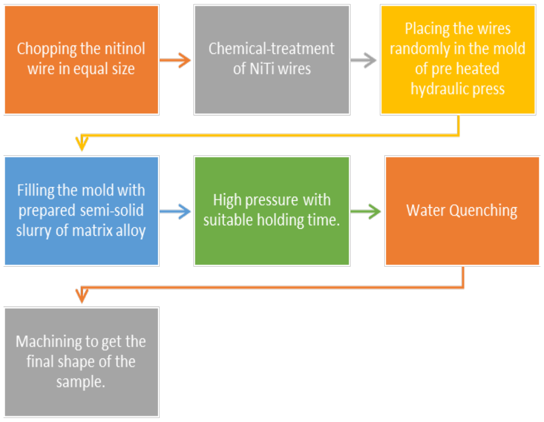


Figure 3. Flow process diagram of the process involved in the preparation of samples.

Nitinol wires were placed into the die randomly after going through surface modification, then the semisolid slurry was poured on top of the fiber bed and high pressure (100 MPa compression) was applied to infiltrate the slurry through the bed of nitinol wires using hydraulic press. The semisolid slurry of matrix alloy was produced with solid fraction of 0.3. The weights of the Mg, Fe, Si, Cu, and Mn were 0.30, 0.20, 6.82, 0.04, and 0.13 all in percentages in A356 alloy as determined by spectroscopy.

The RSF method was used to achieve a globular microstructure of α-Aluminum dendrites by stirring a rod of alloy A356 in a bath of molten 356 using rapid slurry formation method (Figure 4). The RSF technique utilizes enthalpy exchange mass (EEM) to rapidly form a slurry with the desired fraction of solid. In this method enthalpy exchange between different states of (A356) alloy takes place. A calculated mass of enthalpy exchange material is required to maintain the fraction of solids.

The composition of solid EEM was the same as molten material,[17] only the state was different. The pictorial view of the experimental setup for making the squeeze cast samples after pouring the semisolid slurry in the bed of nitinol fibers is shown in Figures 4 and 5.

Figure 4(a) indicates the set-up for preparation of the A356 slurry and Figure 4(b) shows the hydraulic press with the cast iron mold in which nitinol fibers were placed before and pouring semisolid slurry on them, followed by application of pressure. The preparation of semisolid slurry began with placing the billets of A356 alloy in a graphite crucible followed by putting the crucible inside an electrical resistance furnace (Figure 4(a)). The furnace temperature is maintained at 1220F (660C). After the complete melting of the billets, degasification was done.

(a)

(b)

Figure 4. Pictorial view of test setup (a) forming semi-solid slurry of A356; and (b) for making short nitinol fibers reinforced self-healing metal matrix composite structure.[16]

The solid cylindrical bar of A356 was immersed in molten metal and rotated at 35 rpm. After dissolution of the enthalpy exchange mass, grain refiner (Al-5Ti-B) 0.20% and grain modifier Al-10Sr (0.0020%) were added to the semisolid, then it was stirred for 90 seconds for proper mixing. The stirrer rod was removed from the molten metal when the slurry temperature reached 1106.33F (596.85C) and the melt was held for 5 minutes iso-thermally after the lid was closed to allow for the microstructure of α-Al to become more globular due to ripening. The semisolid slurry of A356 was transferred into the heated mold under the hydraulic piston press (the chopped wires of nitinol were already present in the mold). A schematic diagram of the different steps is shown in Figure 5.

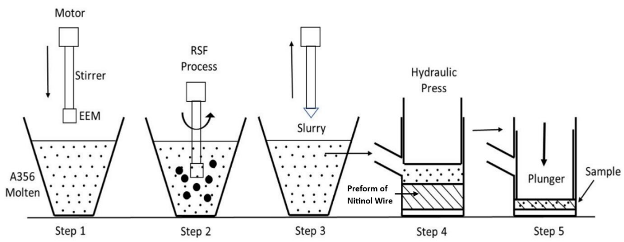


Figure 5. The five step process followed during the Rapid Slurry Formation (RSF) casting technique.[16]

With the help of the plunger in the hydraulic press, high pressure around 100 MPa was applied to form the solid metal matrix composite disc as shown in Figure 6.

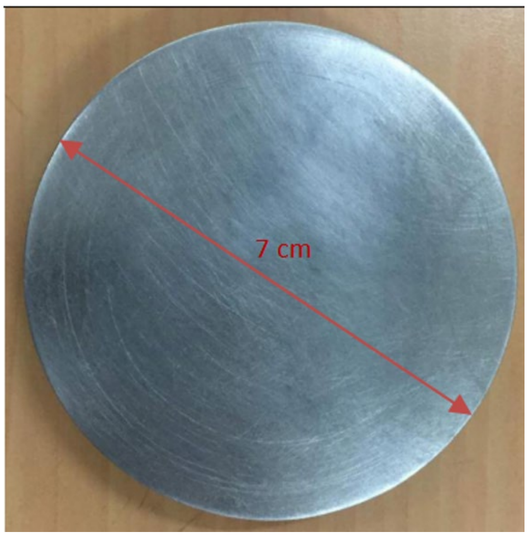


Figure 6. Disc of A356-nitinol composite formed by squeeze casting of the semisolid slurry in the fiber bed.[16]

The disc was heated to 878F (470C) to relieve residual stresses. When the nitinol wire was heated to this specific temperature, it transformed from twinned martensite to austenite, followed by a reversion to martensite upon cooling after stress relieving.

RESULTS AND DISCUSSION

The Rapid Slurry Formation (RSF) technique transformed the dendritic microstructure of α- Al in the A356 alloy into a globular microstructure. Figure 7 shows the diameter of alpha aluminum globular dendrites ranging from 11 microns to 16 microns. This suggests a consistent distribution of transformed globules with an aspect ratio close to 1 within the matrix alloy. Figure 8 shows a cross section of a nitinol fiber embedded in the matrix of A356 alloy showing continuous contact between the surface of the fiber and the matrix.

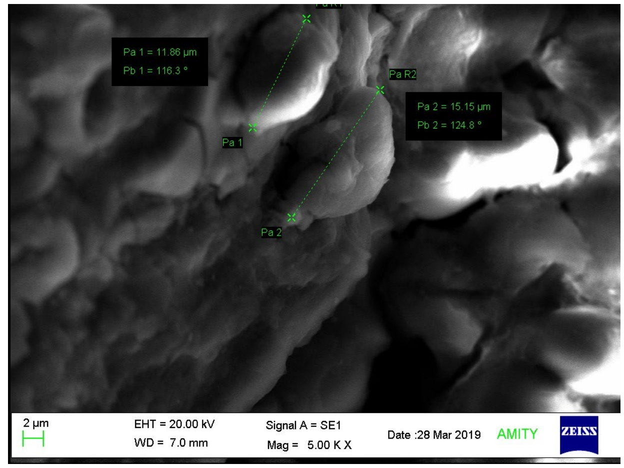


Figure 7. An SEM micrograph showing the globular microstructure of α-Aluminum after processing.

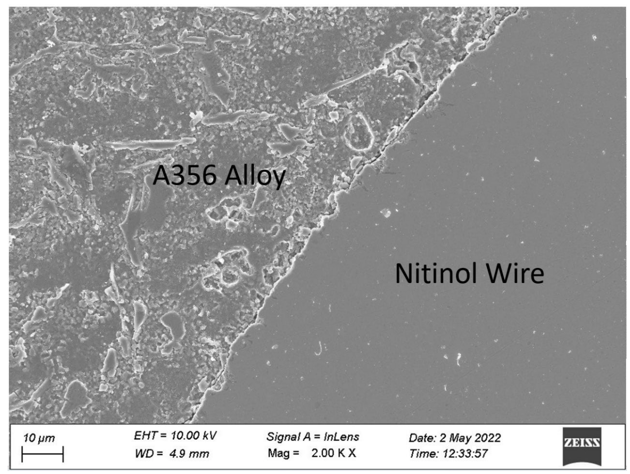
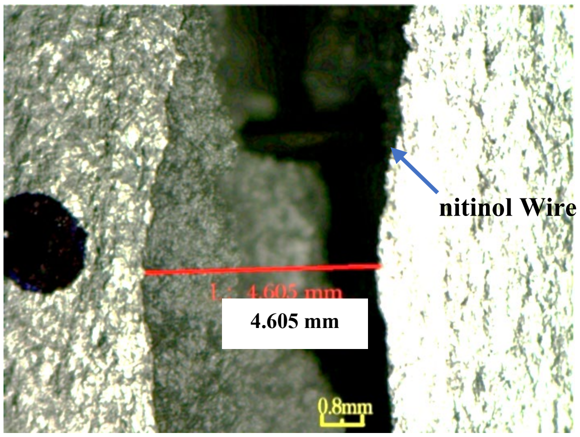
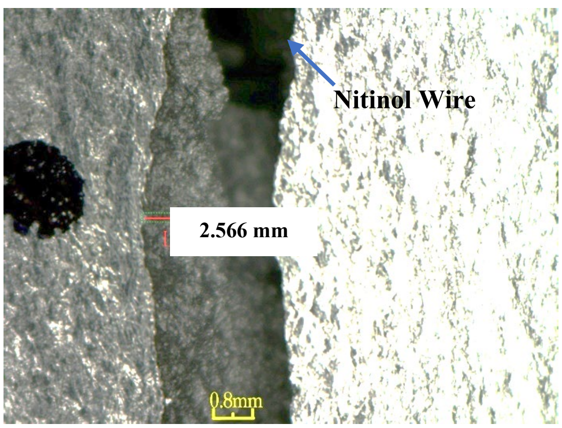


Figure 8. An SEM micrograph shows cross section of nitinol wire embedded in the matrix of A356 alloy in the composite.[18]

The spatial mapping of the elements within the image area revealed the presence of primary aluminum (Al) with a high intensity peak, indicating its abundance within the alloy. Additionally, other alloying elements such as silicon (Si), magnesium (Mg), nickel (Ni), titanium (Ti), and copper (Cu) are detected. The intensity of these elements in the EDX spectrum confirms their presence in A356 alloy. These alloying elements enhance the alloy's strength, corrosion resistance, and other desirable properties. The composite sample was subjected to bending test until it cracked. The crack was 4.605 mm in width. When the temperature of the sample was raised above the transformation temperature of the nitinol wire [specifically 212F (100C)] for 5 minutes, the transformation of martensite to austenite occurred, causing the nitinol wire to shrink.[19] The shrinking wires applied the compressive forces to the crack resulting in narrowing of the crack from 4.605 mm to a width of 2.566 mm as shown in Figure 9.



(a)



(b)

Figure 9. a) wide crack of 4.605 mm after bending (b) after heating the crack reduces in width to 2.566 mm.[16]

CASTING OF SAMPLE BY POURING LIQUID METAL IN PERMANENT MOLDS

Aluminum Alloy A380 Reinforced Nitinol Fibers Metal Matrix Composites

Long nitinol fiber reinforced self-healing metal matrix composites were cast using aluminum alloy A380 (Al-8Si-3.5Cu) as the matrix material.[20] The resulting samples had varying widths, but all measured 10 cm × 1.2 cm. The nitinol fibers used had a diameter of 0.5 mm and were wound around a steel frame made of threaded steel rod with a diameter of 5 mm and 2cm × 2mm steel bars. This assembly is depicted in Fig. 10(a). Both the mold and nitinol fibers wound on steel frame were preheated to 302 F (150C) before pouring the molten matrix, heated to 1742F (950C), into the mold containing the frame and the wound nitinol wires. The threaded rod was kept in the cast sample as an additional load transfer mechanism. The cast sample is illustrated in Figs. 10(a) and (b). Figure 11 is an SEM image for the cast sample showing two nitinol wires embedded in the A380 aluminum alloy matrix.

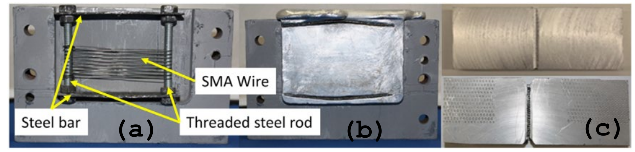


Figure 10. (a) A customized steel frame for wire winding with nitinol wires; (b) cast self-healing structures; and (c) cracked sample under tensile loading.[20]

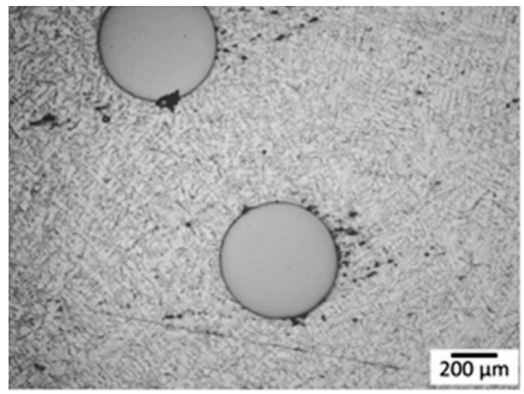


Figure 11. Microscopic view of the cast A380 matrix surrounding two nitinol wires.[20]

A SATEC Model 50Ud Universal Testing Machine was used to apply test tensile load on fabricated samples along the length of the fibers. The middle of the sample had a 45° V-shaped notch to serve as a guide for the crack as shown in Figure 10(c). The samples were tested at a crosshead speed with a strain rate of 10^{-3} s.$^{-1}$

After cracking the sample at room temperature, a Thermolyne FB1300 Heat Treatment Furnace was used to heal the crack composite sample at 455F (235C). To study the rate of crack closure in the damaged sample with a known crack width was placed on a hot plate heated to healing temperatures, and the decrease in area width with time was measured.

Figure 12(a) presents X-ray radiographic images of as cast sample (b) tensile tested sample showing wide crack in the matrix with intact fibers and (c) shows narrowing of the crack as a result of heating for healing, as a result of shrinking of the fibers.

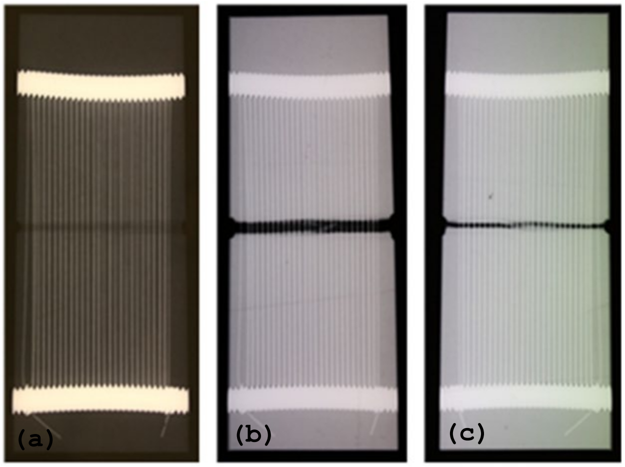


Figure 12. X-ray scanned images of the prepared structure (a) a cast sample; (b) after cracking due to tensile loading; and (c) after heating to healing temperature.[20]

RESULTS AND DISCUSSION

The sample after heating to the healing temperature at 455F (235C) exhibited a 62.963% reduction in the width of the crack, as shown in Figure 13. The reasons for not achieving full closure of the crack could be due to insufficient compressive stresses applied by inadequate volume percentage of nitinol wire and lack of liquid phase at the crack. It is believed that with optimization in the volume percentage and size of fibers and healing temperature the presence of liquid phase would result in complete closure of the crack. The addition of nitinol reinforcement resulted in a two-fold increase in the strength and ductility of cast composites compared to the unreinforced sample as shown in Figure 14. It was also found that the activation time of nitinol fibers and the duration of crack closure increase with the increase in sample size. The crack closure rate decreases with increased sample size.

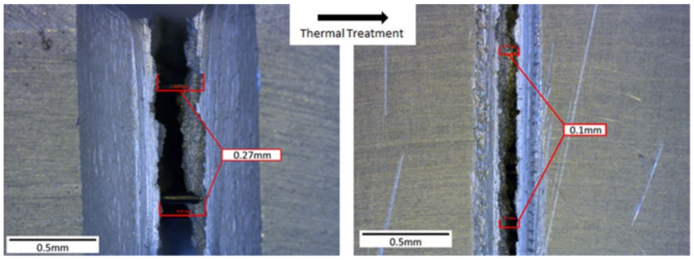


Figure 13. Damaged sample before and after healing during thermal treatment, showing decrease in width of cracks.[20]

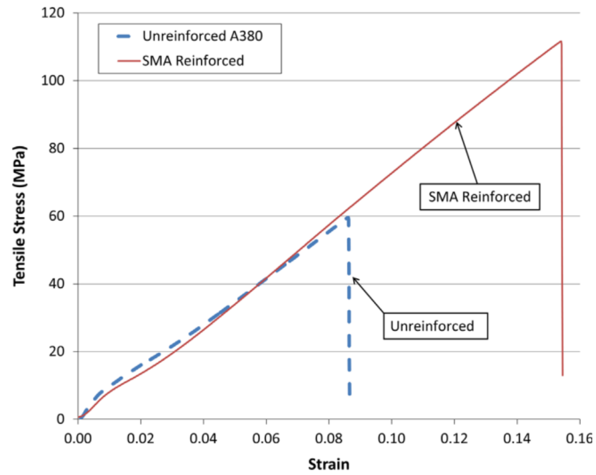


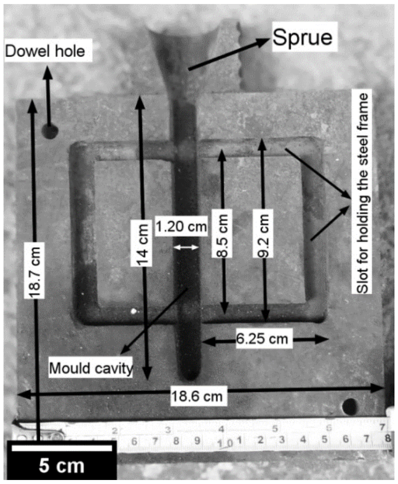
Figure 14. Tensile plot for the cast composites compared to the unreinforced composite sample.[20]

Aluminum Alloy AA2014 Reinforced Nitinol Fibers Metal Matrix Composites.

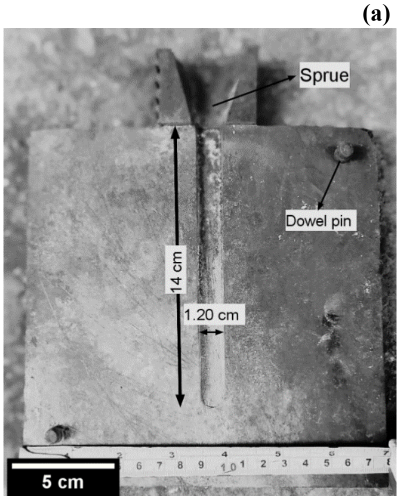
The matrix material selected for this study was aluminum alloy AA2014. This alloy was reinforced with Ni55Ti45 (nitinol) wires, which shrank as they were heated, and narrowed or closed the crack.[21] The nitinol wire, characterized by an austenite transformation temperature of 158F (70C), was used as reinforcement.

A steel mold, composed of two halves was used to cast the composite as depicted in Figures 15(a) and 15(b). A steel frame was created to tightly wind the nitinol wires while under tension, followed by a heat treatment at 923F (495C) for 10 minutes, as illustrated in Figure 15(c).

Subsequently, the steel frame, with the wound wires, underwent a rapid quenching process in water at room temperature 77F (25C) to retain the martensitic phase in the wires, which is the characteristic phase of the wires in their cold state. The mold cavity, containing the wound nitinol wires, was filled with molten AA2014 metal at 1562F (850C), directly through the die's sprue, as shown in Figure 15(d). To protect the reinforcing wires from damage during machining, an X-ray radiographic image was captured of the cast specimen. Following casting, the solidified specimens were machined using a CNC milling machine (HEC43 (G) T) and shaped using a wire electric discharge machine (WEDM) Model EX-7732.



(a)



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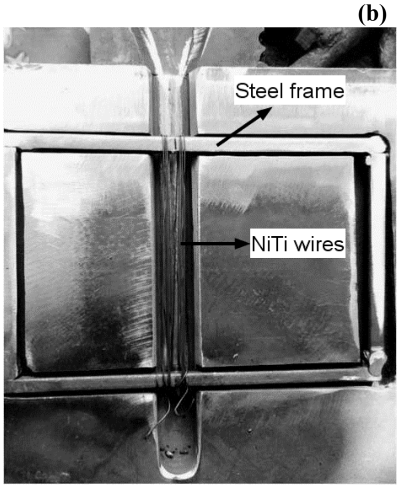
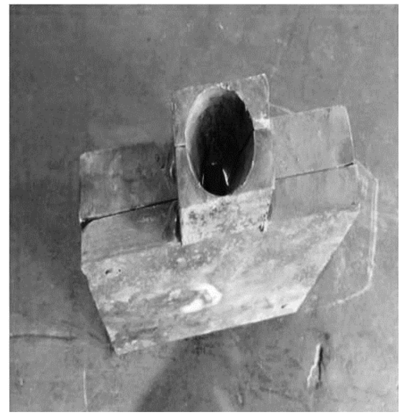


(c)



(d)

Figure 15. (a) and (b) customized steel die components used for gravity casting method; (c) frame employed for winding the nitinol wire; and (d) assembled view of the permanent mold steel die.[21]

The SEM micrograph shows a region of the composite reinforced with five nitinol wires, the respective chemical compositions of the matrix and nitinol fibers were determined using via spot analysis in Figure 16 (a-d). The nitinol wires were in contact with each other due to the procedure used to wind the wires around the frame. The distribution of nitinol wires will influence the self-healing behavior.

The flexural testing of the prepared composite specimens was done in according to the ASTM E399 standard. To facilitate the examination of crack propagation and to direct the crack during bending, a V-notch with a depth of 0.25 mm was machined, passing through the center of each specimen. The flexural tests were carried out using a universal testing machine (Tinius Olsen) with a load capacity of 10 KN, employing a constant strain rate of 0.0166/s.22 When the composite specimens underwent loading, they incurred damage at the yield point, resulting in significant deformation and deflection of their shape. The dimensions of the crack opening were examined using an optical microscope at precise locations both before healing and after healing. The chosen healing temperature of 1076F (580C) was determined to activate the SMA wire for clamping, while at the same time simultaneously inducing liquid assisted compositional healing at the damaged interface. At 1076F (580C) temperature a certain fraction of the matrix liquifies helps in sealing the crack. Subsequently, the healing efficiency, percentage reduction in crack width, and crack depth recovery efficiency were calculated in accordance with Equations 1 and 2.[23] The flexural stress for both the damaged sample and after healing of the sample was calculated using Equation 3.[24]

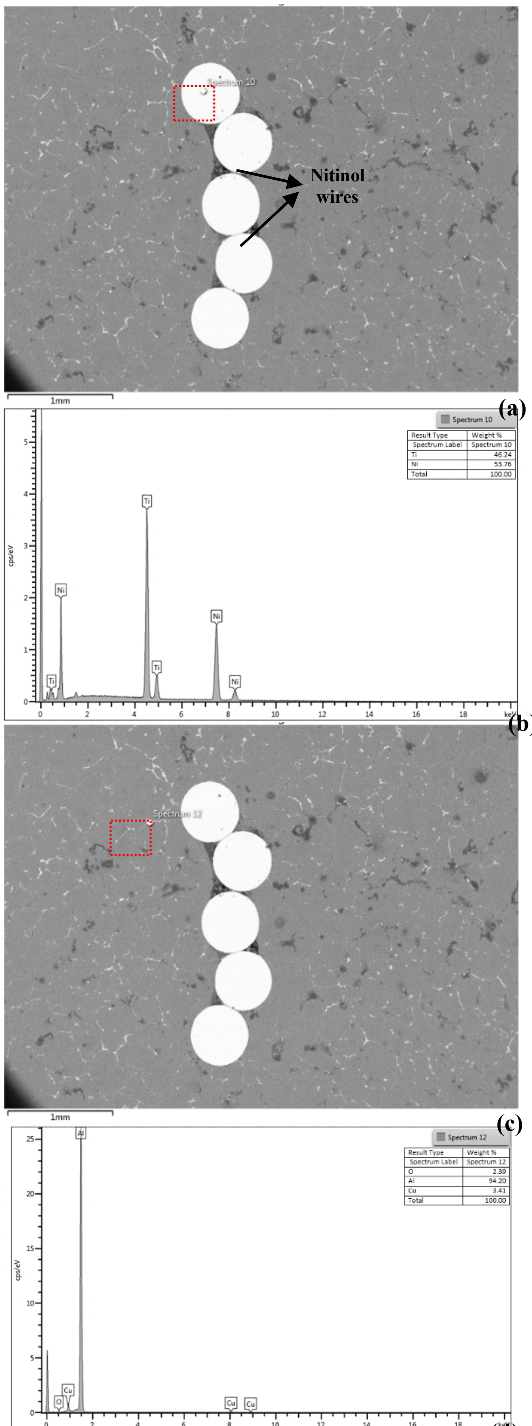


Figure 16. (a) SEM micrograph of reinforced nitinol wire at 30x magnification, with the spectrum taken on the nitinol wire; (b) chemical composition of the nitinol wire through spot analysis (EDX) ; (c) SEM micrograph of reinforced nitinol wire at 30x magnification, with the spectrum taken on the matrix; (d) chemical composition of the matrix through spot analysis (EDX).[21]

$$\alpha_{healing\ efficiency} = \frac{\alpha_{healed\ samples}}{\alpha_{damaged\ samples}} * 100$$

Eqn. **1**

$$\eta_{recovery\ in\ crack\ depth\ \&\ crack\ width} = \frac{\alpha_{before\ healing} - \alpha_{after\ healing}}{\alpha_{before\ healing}}$$

Eqn. 2

Where:
"α" = property of interest (crack width, crack depth, and flexural strength)

$$\sigma_{flexural\ stress} = \frac{3Fl}{2bt^2}$$

Eqn. 3

Where:
F = Flexural Load;
L = Specimen length;
b = Specimen breadth;
t = Specimen thickness

RESULTS AND DISCUSSION

The healing process involves two stages. The first stage includes utilizing the SMA wire's shape memory effect to reduce the width of the crack with compressive force at the damage interface. In the second stage when the sample is heated at 1076F (580C) around 15% of the matrix (primarily the eutectic) is turned into liquid phase according to Al-Cu binary phase diagram using lever rule. The partially melted matrix flows down to the crack through capillary action and surface tension, and improves the bonding and sealing of the surfaces.[25] These two processes, together help repair, close and seal the crack. A reduction in crack width efficiency of approximately 84.01% was noted for the sample, which was reinforced with a 0.46 mm diameter wire containing 0.50 vol. % of nitinol wires and subjected to a 120-minute healing process at a 1076F (580C) healing temperature in a muffle furnace as shown in Figure 17(a). Complete crack closure was achieved with an AA2014 matrix reinforced by a column of solder alloy (Sn60Pb40) and 0.50 vol. % nitinol wires. In addition, a complete recovery from flexure tested deformed shape to the original straight shape was observed during thermal treatment as shown in Figure 17(b). With increase time of healing, there is an increase in crack width healing efficiency. It was observed Figure 18(a) that a longer duration allows for more time to the liquid fraction of the matrix alloy (eutectic phase) to fill the crack. Consequently, the infusion of this liquid composition into the crack interface leads to a substantial increase in healing efficiency.

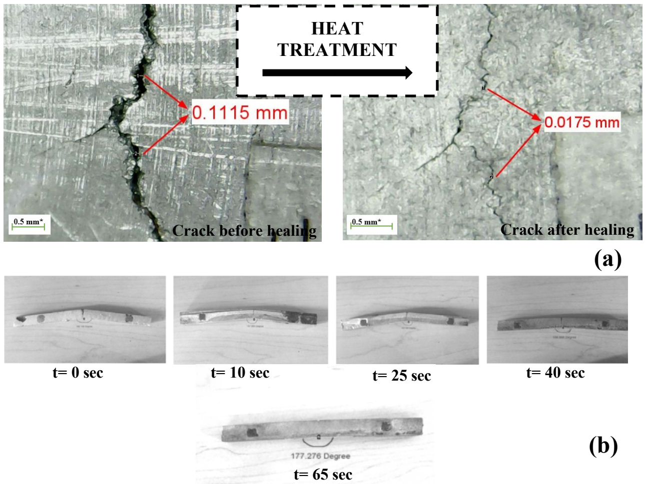
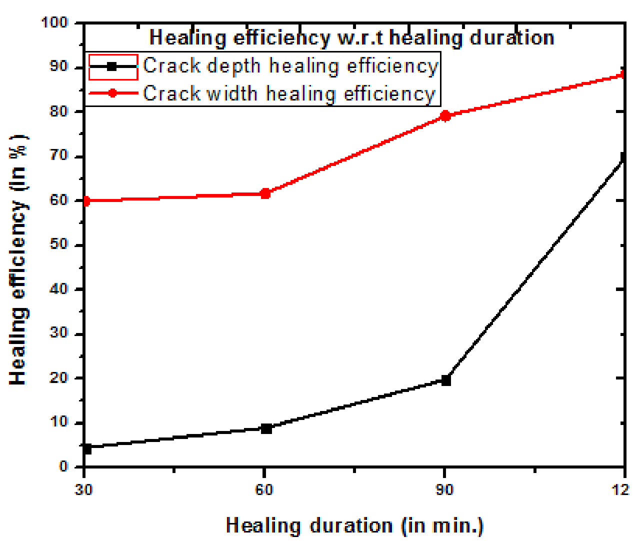
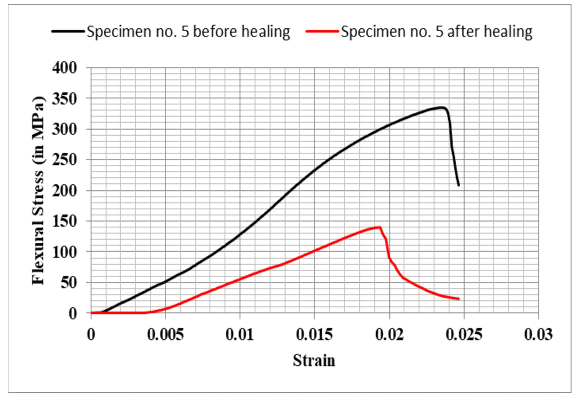


Figure 17. (a) reduction in width and closing of the crack of the deformed and bent sample and repair of a damaged structure after thermal treatment; and (b) recovery in shape after healing, the bent bars straightens upon heating.[21]

Evaluating flexural strength recovery after heat treatment is crucial for assessing the structural functionality, as strength plays a significant role in its performance. The sample under identical conditions achieves the highest strength recovery, reaching approximately 44.18% as can be observed in Figure 18(b). Both healing mechanisms, shrinking of SMA wires and liquefaction of eutectic phase in the matrix, and its flow to the crack work to securely heal the crack interface. Table 1 summarizes the self-healing efficiencies achieved with three different matrix materials, two different casting techniques, and two states of stress.



(a)
Figure 18. (a) A graph includes the effect of healing duration on healing assessments.[21]



(b)

Figure 19. (b) recovery in Flexural strength for the healed sample.[21]

CONCLUSIONS

1. Rapid slurry formation was used to make a slurry of Al alloy A356 and this slurry was squeeze cast into the bed of discontinuous nitinol fibers. The casting was cracked under bending loading conditions and the crack was 44.27 % narrower after heating the cracked sample.
2. A melt of Al alloy A380 was poured onto a nitinol wire wound on a steel frame in a permanent mold. The crack formed under tensile loading was narrower by 62.96 % after heating above the transformation temperature to shrink nitinol fibers.
3. Gravity casting was used to cast continuous nitinol fiber reinforced with aluminum alloy AA2014 which showed crack closure, self-healing, and around 45% of strength recovery after cracking under bending loading conditions.
4. Optimizing the volume percentage of nitinol fibers, their diameters, and surface treatment can lead to an aluminum casting in which cracks can be narrowed or completely closed as a result of self-healing.
5. Casting is becoming a preferred processing route for self-healing metal matrix composites.
6. Gravity casting and squeeze casting after rapid semisolid slurry formation can be used to form self-healing aluminum alloy-SMA-based composites.
7. Incorporation of 0.50 % vol. of nitinol of diameter 0.46 mm in AA2014 matrix enables almost complete closure of the crack and narrowing of the crack after heating.
8. Self-healing aluminum matrix composites synthesized by gravity and semisolid casting would be useful in aerospace, automotive, and offshore applications enhancing the life of components and safety. Their use in electronics can lead to more robust electronic circuits, reducing failure rates.

Table 1. Comparison of Casting Methods and Matrix Materials on Healing Properties of Composites

Matrix	Healing agent	Casting method	Mechanical Testing	Healing results
A356	Nitinol fibers (Discontinuous) Wire Dia. 0.50 mm	Rapid Slurry Formation	3-Point Bend Test	44.27 % Reduction in crack width
A380	Nitinol fibers (Continuous and Unidirectional) Wire Dia. 0.50 mm	Permanent Die Gravity Casting	Tensile Test	62.96 % Reduction in crack width
AA2014	Nitinol fibers (Continuous and Unidirectional) SMA Vol. % 0.50, Wire Dia. 0.46 mm	Permanent Die Gravity Casting	3-Point Bend Test	84.30 % Reduction in crack width and 45% of strength recovery

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