

Optimal design of a bio-inspired self-healing metal matrix composite reinforced with Ni-Ti shape memory alloy strips

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Abstract

Utilizing smart materials such as shape memory alloys as reinforcement in metal matrix composites is a novel method to bio-mimic self-healing. This study aims to investigate the influence of design factors of a self-healing metal matrix composite by employing the Taguchi method for designing of the experimental procedure. Three design factors, each in three levels, was studied simultaneously according to L9 standard Taguchi orthogonal array to determine the optimal level of each factor in mechanical properties enhancement with a reduced number of experiments. Composite specimens were fabricated from Sn-13 wt.% Bi alloy as matrix and nickel-titanium shape memory alloy (SMA) strips as reinforcement with gravity casting process. Matrix alloy was melted and casted in a preheated metallic mold in which SMA strips were installed in various quantities (1, 2 or 3 strips) and different pre-strains (0, 2 or 6 percent). After fabrication of the specimens, a tensile test was conducted until fracture to specify mechanical properties. Then specimens were placed in a furnace in three different temperatures (170, 180 and 190 °C) to activate the shape memory effect of strips and achieve crack closure and healing. Specimens were tensile tested again after healing to calculate the amount of healed properties and healing efficiency. Results show that using three strips with 6% of pre-strain and applying 190 °C healing temperature can maximize the ultimate tensile strength efficiency. Also, the existence of 1 strip, 0% pre-strain and 190 °C healing temperature creates the best circumstances for healing ductility.

Keywords: Metal matrix composite, Tin-Bismuth-Ni/Ti composite, Shape memory alloy, Self-healing, Taguchi method

1- Introduction

Creating self-healing materials was a dream inspired by the ability of biological systems to repair and heal injuries and damages. In order to clarify the mechanism of self-healing, several researchers worked on modeling self-healing phenomena in various living organs in nature (Fratzl and Weinkamer, 2007; Vermolen et al., 2007). This dream nowadays came true by using several methods in different sorts of materials such as polymers, ceramics and recently in metallic materials (Ghosh, 2009; Habault et al., 2013). It has been proven that polymer matrix composites are the most successful materials to establish the self-healing characteristic (Van der Zwaag et al., 2009). The most conventional way to induce the ability to heal voids and cracks autonomously is embedding liquid phase healing agent inside the material during fabrication (Wang et al., 2015). Embedment of the healing agent can be accomplished through several methods such as microencapsulation in which self-healing functionality was achieved by placing microencapsulated healing agent and a catalytic chemical trigger within a polymer matrix (Kessler, 2007; White et al., 2001; Jin et al., 2012). Another approaches involve installing hollow glass fibers or microvascular networks filled with resin and hardener, inside the specimen so when a crack starts to grow and break the fiber's fragile wall and release the healing agent into the crack (Nishida, 2013; Kousourakis and Mouritz, 2010; Toohey et al., 2007; Hamilton et al., 2010).

The most significant researches in the area of self-healing metallic materials can be categorized into three major procedures. The first method involves solid state healing of microcracks based on atomic diffusion (Lumley and Polmear, 2007). In this method dynamic precipitation of alloying elements in the surface of microcracks walls plays a critical role in

order to change crack surface properties and stop crack grows which can lead to failure (Shinya et al., 2006; Shinya et al., 2003; Lumley et al., 2002; Lumley and Schaffer, 2006; ASTM, 2009; Fisher and Manuel, 2012; Laha et al., 2007). Although solid state healing showed a promising capacity to heal micro-cracks and stop creep damage, it was unable to heal macroscopic defects.

Inspired by liquid assisted self-healing in polymeric materials, another approach that was used in metallic materials is to embed low melting point solder alloys within hollow fibers and microcapsules inside the metallic matrix (Ruzek, 2009; Lucci et al., 2008b; Lucci et al., 2008a). Due to the availability of enough liquid healing agent at elevated temperatures, this method achieved acceptable results in healing of pinholes and some macrocracks, but it was unable to restore the pre-failure shape of the specimens, so in cases that crack surfaces kept aloof of each other, healing was not possible.

To overcome this deficiency, shape memory alloy (SMA) reinforcement was introduced by scholars (Manuel and Olson, 2007; Fisher, 2013; Hyer, 2009). SMA reinforcement satisfies the required conditions to accomplish both shape recovery and crack clamping and closure. Therefore, by choosing a matrix alloy composition that is partially molten near the SMA transformation temperature and applying required heat treatment, crack surfaces would be re-joined, rebounded and crack healing would be accomplished (Kirkby et al., 2008; Hassan et al., 2013; Habault et al., 2013).

Manuel and Olson (Manuel, 2007) fabricated self-healing metal matrix composite by using 1vol.% of nickel-titanium (NiTi) SMA continuous wires that were aligned uniaxially as reinforcement in Sn-based and Mg-based metallic matrixes. The experimental procedure involved tensile testing of the standard specimens at room temperature until rupture of matrix alloy happens but SMA wires still bridge the crack. During the first tensile test, pre-heal mechanical properties were calculated, and then heat treatment at healing temperature was

applied to activate SMA phase transition, partially melting the matrix alloy and heal the crack.

After healing heat treatment, the second tensile test was conducted to determine the amount of recovered mechanical properties. By dividing the amount of a specific property after healing to the amount of that same property before heal, healing efficiency has been calculated. Manuel achieved 95% recovery of ultimate tensile strength (UTS) by employing this method in Sn-based self-healing metal matrix composite. Although UTS recovery depicted an outstanding retrieval, the ductility of the healed specimens displayed a significant reduction compared to original value.

Misra (Misra, 2013) explored similar approach as Manuel to fabricate a self-healing metallic composite with Sn-based matrix but in different loading condition (bending) and various matrix compositions. His study concentrated mostly on fabrication procedure and microstructural investigation of the healing phenomena. Rohatgi (Rohatgi, 2014) employed SMA wires as reinforcement to form a self-healing Al-SMA composite which was manufactured by casting Al-A380 in a mold that contained SMA reinforcements wrapped around two rods. He fined the rate of crack closure to depend on the dimension of the specimens rather than the number of wires installed in the mold. Although the gap distance between crack surfaces was reduced in this study, the absence of rebonding between crack surfaces the specimens did not recover their strength.

Ferguson (Ferguson et al., 2015) used zinc alloy ZA-8 as matrix and NiTi SMA reinforcement with a similar fabrication process as Rohatgi and formed a metal matrix composite. In this survey, even though the specimens were healed and recovered a fraction of strength and ductility of the completely fractured specimens, but it was essential to use a sand case as support for maintaining structural stability. Also due to lack of effective bonding in the interface of SMA wires, it was necessary to use a bolt embedded within the matrix to twist

SMA wires around it and transfer compression load effectively. Zhu (Zhu et al., 2016) used finite element method with ABAQUS to model a three dimension 3 point bending specimen of a self-healing metal matrix composite reinforced with SMA wires and demonstrated that using SMA wires can provide required force to close the crack and clamp crack surfaces.

Lack of a comprehensive study on the effect of involved parameters of fabrication and healing on self-healing efficiency of metal matrix materials was the driving force for the current investigation. The previous literature contains research on the self-healing metal matrix composites with specific fabrication conditions and healing circumstances. In this study, the influence of various fabrication and healing parameters on the effectiveness of the healing process was investigated. These parameters include during production specifications such as volume fraction of the SMA reinforcement and pre-strain of the reinforcement or healing parameters like healing temperature. Because there are too many parameters to study and each parameter can differ in quantity and possess different levels it is economically inefficient and time-consuming to study all of them one by one. To avoid this problem and study all of the uppermost parameters simultaneously, the design of the experiment by Taguchi method was employed, and three parameters each in three levels were experimentally investigated. SMA strips volume fraction varied for 1, 2 and 3 strips, 0, 2 and 6 percent of the pre-strain was considered, and healing temperature differed between 170, 180 and 190 °C.

2- Materials and method

2-1- Materials

Commercial pure tin and bismuth elements (99.8%) were used for fabrication of matrix alloy with a composition of 87 wt.% tin and 13 wt.% bismuth. Nickel-titanium shape memory

alloy strips with a rectangular cross-section ($0.762 \text{ mm} \times 0.254 \text{ mm}$) and a composition of 45.5 wt.% Ti, and 54.5 wt.% Ni were provided from Confluent Medical Technologies Company (CMTC, 2016). The A_s , A_f , M_s and M_f temperatures of SMA strips are 76, 110, 60 and 47 °C, consecutively and with a recoverable shape memory strain of 8%, they were used as composite reinforcement to synthesize rectangular tension test specimens. The strips were reduced to martensite final temperature and were cutted in room temperature with the twinned initial state. Since the deformed shape of the strips was not required in the healing process, the one-way shape memory strips were employed.

The reason of using SMA strips rather than SMA wires was the fact that there was a limit for the number of wires that could be installed inside the mold due to unavailability of enough room and by using strips instead of wires, it is possible to achieve higher SMA volume fractions. The internal fixtures that were designed inside the mold to hold the reinforcement had a limitation on the number of wires or strips that they can hold. Another reason is that in an equal volume fraction matrix-reinforcement interface surface is higher when a rectangular cross section strip is used instead of round wires and since the interface surface plays a critical role in the transformation of force from SMA reinforcement to matrix alloy, it is essential to maximize the interface surface.

2-2- Fabrication process

The most conventional methods to fabricate metal matrix composites are powder metallurgy, casting or liquid infiltration and spray co-deposition (Chawla, 2006). Due to the low melting point of the Sn-Bi matrix alloy and availability of equipment, the casting was chosen to produce the specimens. Since the SMA strips should be embedded uniaxially and continuously, a custom-made metallic mold was designed as Figure 1 and manufactured with

internal fixtures to put SMA strips in desired position and direction. Path “A” shows the position of the mounted SMA strips along the specimen and in between the fixtures.

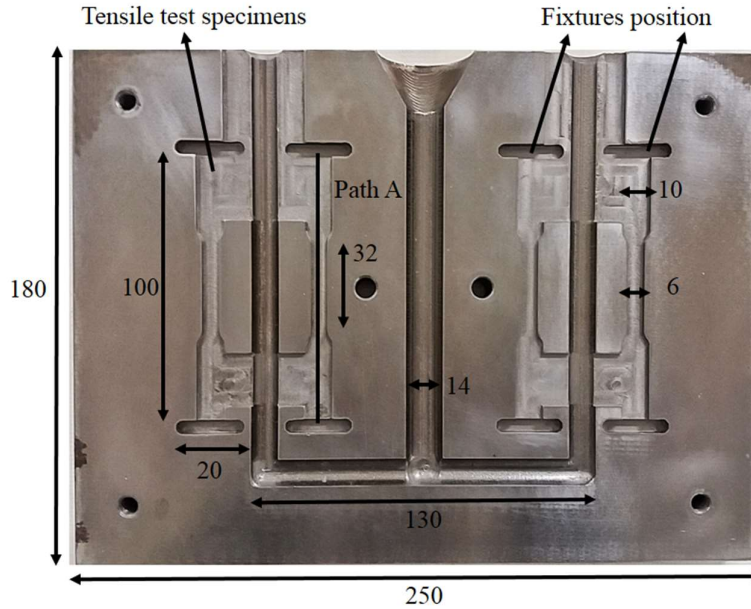


Figure 1. Designed mold with internal fixtures (all dimensions are in mm).

Prior to casting, the mold was preheated, and the cavity was coated with graphite spray. This coating creates a smooth flow of the melted Sn-Bi alloy through the cavity and also easy ejection of the specimens from the mold. SMA strips have been trained straight but were wrapped around a tube during transportation. So at first strips were heated above the austenitic temperature to remove the effect of previous deformations and residual stresses. After this primary heat treatment, strips were chopped in specific lengths and pulled with the tensile testing machine to reach the stated pre-strains (0, 2 and 6 percent). Since during pre-heating the mold, the strips were clamped at both ends by the internal fixtures, there were no reduction in pre-strain due to applied temperature. The configuration of the SMA strips inside the mold and within the cross section of the specimens is demonstrated in Figure 2.

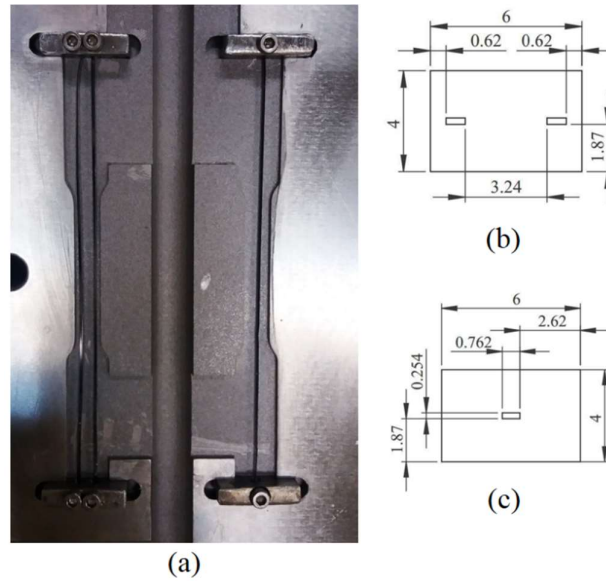


Figure 2. The configuration of the SMA strips embedment, a) one and two strips inside the mold, b) cross-section of the specimen with two strips, c) cross-section of the specimen with one strip.

Before placing the SMA strips in the mold, a critical point to be considered is the formation of a very stable titanium oxide layer around the strips which embrittles the strip-matrix interface. This oxide layer disables the effective load transfer between SMA strips and matrix and extremely reduces the strip surface wettability that leads to the formation of a poor interface (Misra, 2013). The resultant pressure of load transfer between strips and matrix alloy is an essential part of crack closure and healing. Some researchers (Rohatgi, 2014; Ferguson et al., 2015) used the second part like a screw to wrap the SMA reinforcement around it and placed the screw inside the specimen to ensure effective load transfer but this method cannot be used in all applications and would weaken the part of specimen in which screw is embedded.

As explained, the formation of the oxide layer leads to embitterment of the matrix-fiber interface, and this causes a significant reduction in transferable force between them. This reduction in interface strength leads to matrix-strip separation in the healing process, especially

in high pre-strained specimens that disable the healing mechanism. Therefore, to avoid these problems, the oxide layer in the surface of strips must be removed. Scholars proposed different methods to remove the oxide layer. Since magnesium oxide is more stable of titanium oxide, Manuel used Mg-based alloys as the matrix. Manuel also used electrochemical etching the SMA wires and then sputter coating them with Au (Manuel, 2007). Coating wires with Cu (Martinez-Lucci et al., 2011) and using etchant to remove the titanium oxide layer (Coughlin et al., 2009a; Coughlin et al., 2009b) are other methods used to improve the wettability of the SMA surface.

Since chemical etching is the most effective solution to resolve the oxide layer and does not have the destructive effects of coating with Cu and Ni (like demolishing the interface layer during heat treatment cycles due to atomic diffusion (Dutta et al., 2004)), it was employed in this study. So the strips were dipped in an aquatic solution of 4.8% HF – 10.5% HNO₃ for 5 minutes (Coughlin et al., 2009a). Using this chemical etchant not only removes the oxide layer around the strips but also helps to the creation of a strong bond between strips and matrix alloy by roughening the strips surfaces (Misra, 2013). The effect of using this procedure on the formation of a strong interface is shown in Figure 3 by using an optical micrograph of the area surrounding SMA strips.

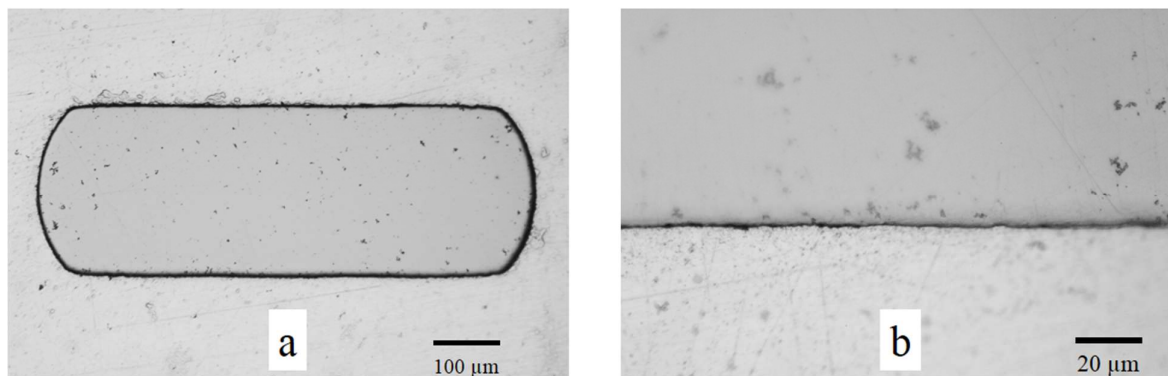


Figure 3. Optical micrograph of the area surrounding SMA strips, a) 10x magnification, b) 50x magnification.

Continuation of casting procedure includes melting tin and bismuth elements in a stainless steel crucible in a furnace at 300 °C with the Sn-13 wt.% Bi composition. The melted alloy was casted in the mold, and after slow solidification, the specimens were ejected out of the mold. These specimens were homogenized to eliminate the matrix dendrite microstructure after casting and then were tensile tested until complete fracture of the matrix alloy.

Tensile tests were conducted according to ASTM-E08 (ASTM, 2009) standard test method for tension testing of metallic materials and by using the Hounsfield H25KS universal testing machine. Subsize rectangular tension test specimens with a gauge length of 25 mm and a cross section of 6 mm × 4 mm were tested at 2 mm/min constant crosshead speed. During tensile test, since the SMA strips had much bigger strength than the matrix alloy, first matrix failure happens but SMA strips will experience recoverable phase transformation and would bridge the crack. Here, the matrix is fabricated with a composition of Sn – 13 wt.% Bi by casting. This composition showed an ultimate tensile strength (UTS) of 70 MPa (Manuel and Olson, 2007) while UTS of NiTi strips that were used as reinforcement is 1070 MPa which is more than 15 times larger than the UTS of matrix alloy. This ratio represents a state of failure mechanism including matrix cracks, crack bridging and local fiber debonding which was confirmed in previous observations (Poormir et al., 2018).

2-3- Healing mechanism

The conceptual healing mechanism includes heat treatment of the fractured specimens to a temperature in which SMA austenitic transformation is complete, and the matrix alloy

reaches to a solid-liquid two-phase region. This temperature is called the healing temperature. Completion of the austenitic transformation makes it possible to ensure crack closure due to applied compression force by SMA strips that experienced local deformation and stress-induced martensite phase along the fracture area (Poormir et al., 2018). When the matrix alloy reaches to matrix alloy two-phase region of the phase diagram, a melted fraction of the matrix provides the liquid healing agent. This process is schematically depicted in Figure 4.

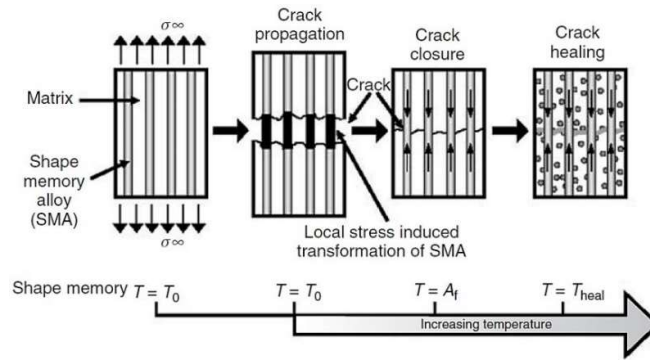


Figure 4. Schematic of a liquid-assisted self-healing metal matrix composite (Ghosh, 2009).

As shown in Figure 5 matrix alloy composition was chosen in a manner that maximizes the difference between eutectic and liquidus temperature. Since in this composition fluctuations in healing temperature has a smaller influence on the liquid fraction of the matrix alloy, better control on the melted fraction of the matrix during the healing process would be provided. So it is easier to investigate the effect of various matrix alloy liquid fractions in the two-phase region by choosing different healing temperatures.

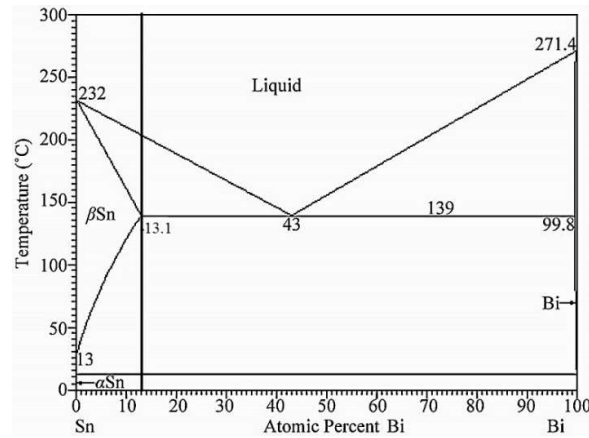


Figure 5. An indication of the matrix composition by using the Sn-Bi phase diagram (Manuel, 2007).

The experimental procedure includes three main steps. In the first step, fabricated specimens after casting were tensile tested until matrix rupture. The second step includes 24 h of healing heat treatment in an atmosphere controlled furnace. The third step is another tensile test from the specimens that were healed previously to determine post-healing mechanical properties to calculate the healing efficiency of each mechanical property.

The healing phrase in the mentioned labels refers to the step 2 which is healing heat treatment and therefore, “before heal” means the mechanical properties that were calculated from the tensile tests at first step and “after healing” indicates the mechanical properties that were calculated from the tensile tests at the third step.

2-4- Design of experiment

Lots of parameters, either in fabrication process or healing procedure, can affect self-healing efficiency of the composite specimens. These parameters include SMA reinforcement volume fraction, the composition of the matrix alloy, pre-strain of the SMA strips, healing temperature and so on. In this study reinforcement volume fraction, SMA strips pre-strain and

healing temperature were considered to be the main parameters effecting self-healing efficiency. Each parameter was investigated in three different level. Reinforcement volume fraction for 1, 2 and 3 strips (0.78, 1.55 and 2.33 percent), SMA strips pre-strain for 0, 2 and 6 percent pre-strain and healing temperature for 170, 180 and 190 °C were chosen for study. Volume fraction (vol.%) of each specimen was calculated according to equation 1. In this equation, V^F , n , S_f and S_c represent volume fraction of the strips, number of the strips, the cross section area of the strips and the cross section area of the specimen (Hyer, 2009).

$$V^F = (n \cdot S_f / S_c) \times 100 \quad (1)$$

These levels were chosen due to limitations with the number of strips each fixture could hold and the recoverable shape memory strain of the SMA strips. Healing temperatures were chosen in a range that would create a two-phase liquid-solid matrix with a liquid fraction more than 20 percent so the healing agent would be enough for the healing process. Near eutectic temperature, there is not enough liquid fraction for rebonding the crack surfaces (Manuel, 2007). Table 1 shows the selected parameters and their levels.

Table 1. Selected parameters and their levels.

Parameter	level 1	level 2	level 3
Volume fraction (vol.%)	0.78	1.55	2.33
Pre-strain (%)	0	2	6
Healing temperature (°C)	170	180	190

In the design of experiment (DOE) subjects, “full factorial” is an experiment in which all of the possible combinations of the involved parameters would be studied. When the number of involved parameters and levels multiplies, examination of all the possible combinations would be time-consuming, costly and sometimes impossible. Taguchi method is a powerful DOE approach which helps to study the effect of several parameters with various levels on the

outcome of the experiment with a reduced number of required examinations. In this study with three effecting parameters, each in 3 levels, the full factorial experiment requires 27 different examination while Taguchi method proposes using an L-9 orthogonal array to study whole parameters simultaneously only with nine examination (Roy, 2010). Minitab 17 statistical software was used for data analysis. The L-9 standard orthogonal array used for conducting experiments is shown in Table 2.

Table 2. The L-9 standard orthogonal array used for conducting experiments.

Specimen No.	Volume fraction (vol.%)	Pre-strain (%)	Healing temperature (°C)
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

From tensile tests, two major mechanical properties including UTS and ductility were calculated. Self-healing efficiency was obtained by dividing the amount of the property after healing (ah index) heat treatment to the amount of that property before healing (bh index). Equations 2 and 3 show the formula for calculation of ultimate tensile strength healing efficiency (η_s) and ductility healing efficiency (η_d), respectively.

$$\eta_s = (UTS_{ah}/UTS_{bh}) \times 100 \quad (2)$$

$$\eta_d = (D_{ah}/D_{bh}) \times 100 \quad (3)$$

The recipe for calculation of ductility involves deriving stress-strain curve from force-displacement diagram using gauge length and the cross-section area of the specimens. After that by employing trapezium numerical integral method, the area under the stress-strain curve which represents ductility can be calculated.

Based on the physical circumstances, in Taguchi method, quality characteristic (QC) can be defined for each property including ultimate tensile strength or ductility either as smaller-better, larger-better or nominal-better. For every one of these QCs, there is a different formula to calculate mean square deviation (MSD) and signal to noise ratio (SN). According to Taguchi method, the level in which SN ratio is maximized would be the efficient level of that parameter. Since the aim of this study is increasing healing efficiency, larger-better QC formulation was employed for both ultimate tensile strength and ductility healing efficiency. SN ratio was calculated using equation 4 in which n represents the number of experiments and y is the output data (Roy, 2001).

$$SN = -10 \log[MSD] = -10 \log \left[\frac{1}{n} \sum_{i=1}^n 1/y_i^2 \right] \quad (4)$$

In terms of design of experiments, when two or more levels in a factor need to be compared, the F-test can be conducted. Although the F-test can produce results for determination of the significance of factor levels similar to the signal to noise ratio by using MSD values of each parameter, there is a different approach adopted in the calculation of F-test values and therefore, studying signal to noise ratio for investigating the significance of each factor is satisfactory.

3- Results and discussion

For each specimen, the stress-strain curve was obtained from a tensile test and dimensions of the specimen. According to the stress-strain curve and by determination of ultimate tensile strength and ductility and using equations 2 and 3, self-healing efficiency was calculated. Self-healing efficiency of each mechanical property was entered and analyzed individually by Minitab and mean effect plots and signal to noise ratio were calculated by a Taguchi data analysis. Figures 6 to 8 show stress-strain curves of three different specimens before and after healing.

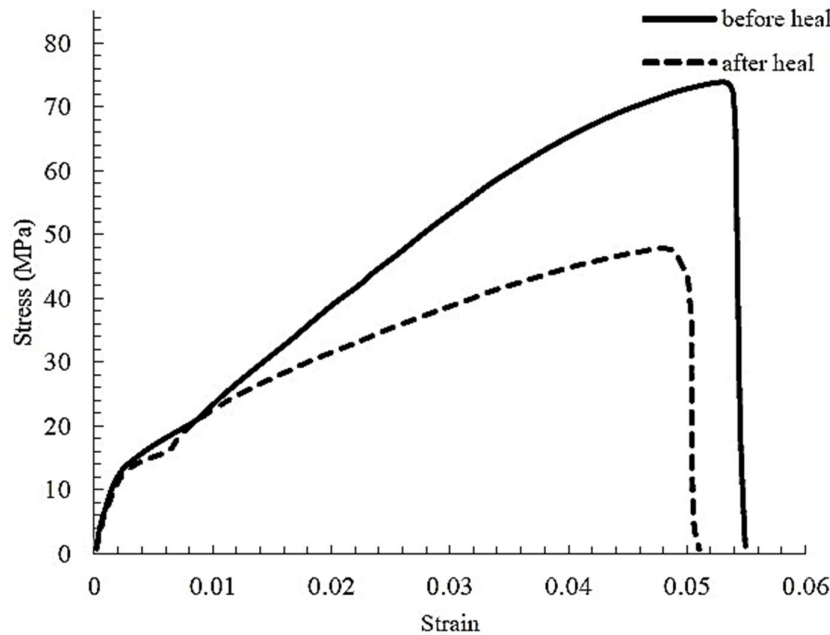


Figure 6. Stress-strain curve of the specimen 2 with a volume fraction of 0.78 vol.%, 2% pre-strain and 24 h heat treatment at 180 °C healing temperature.

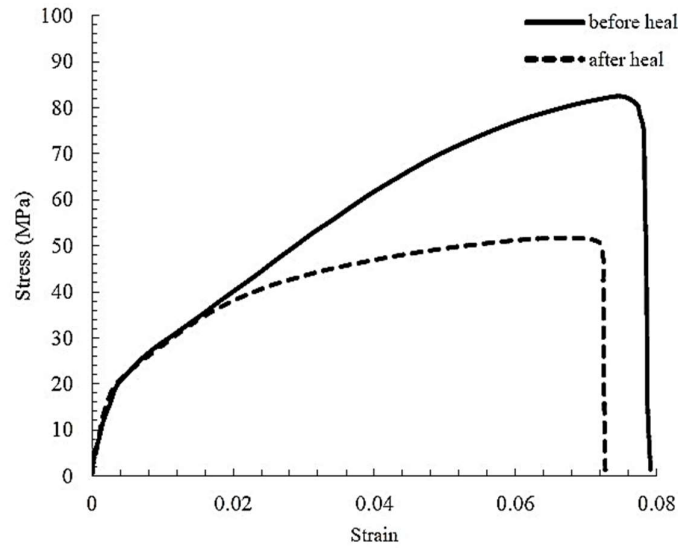


Figure 7. Stress-strain curve of the specimen 5 with a volume fraction of 1.55 vol.%, 2% pre-strain and 24 h heat treatment at 190 °C healing temperature.

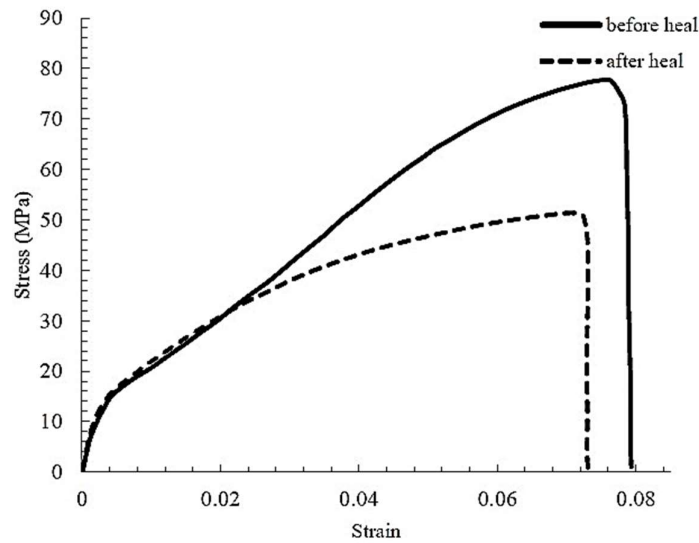


Figure 8. Stress-strain curve of the specimen 9 with a volume fraction of 2.33 vol.%, 6% pre-strain and 24 h heat treatment at 180 °C healing temperature.

In these curves, the point that specimen experienced maximum stress is the ultimate tensile strength and the area under each curve represents ductility. Figure 9 shows the specimen one

before and after healing heat treatment. Marked area in Figure 9, points out to the section that specimen rupture occurred and then healed.

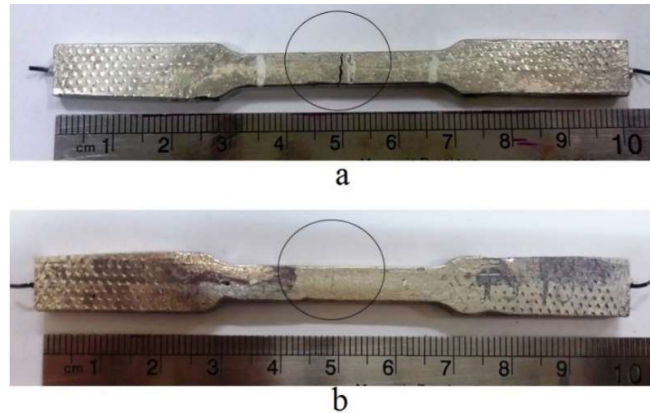


Figure 9. Standard tensile test specimen 1 with a volume fraction of 0.78 vol.%, zero pre-strain and 24 h heat treatment at 170 °C healing temperature, a) before heal, b) after heal.

3-1- Ultimate tensile strength

Table 3 presents the amount of UTS before and after healing and healing efficiency corresponds to each specimen. The overall means of all nine specimen's UTS before and after heal was 78.88 MPa and 49.52 MPa, respectively. Also, an average UTS healing efficiency of 62.77% was achieved in which the highest healing efficiency was 66.08% from specimen 9, and the lowest healing efficiency was 57.25% from specimen 1.

Table 3. Experimental results of ultimate tensile strength.

Specimen No.	UTS before healing (MPa)	UTS after healing (MPa)	Healing efficiency (%)
1	80.04	45.82	57.25
2	73.81	47.81	64.77
3	71.63	46.21	64.51
4	73.93	43.41	58.72
5	82.47	51.68	62.66
6	83.16	54.71	65.79
7	82.07	51.28	62.48
8	85.16	53.40	62.70
9	77.69	51.34	66.08

To analysis effect of each parameter on UTS healing efficiency, a Taguchi analysis was performed according to the larger-better quality characteristic. Resultant influence of every parameter was investigated using mean effect plot as depicted in Figure 10 and signal to noise ratio data in Table 4. According to Table 4, the most effective parameter in UTS healing efficiency is pre-strain of the SMA strips because it creates the largest difference in SN ratio values of different levels (0.84). After pre-strain, the volume fraction of reinforcement and healing temperature stand in the next positions of effectiveness on healing efficiency.

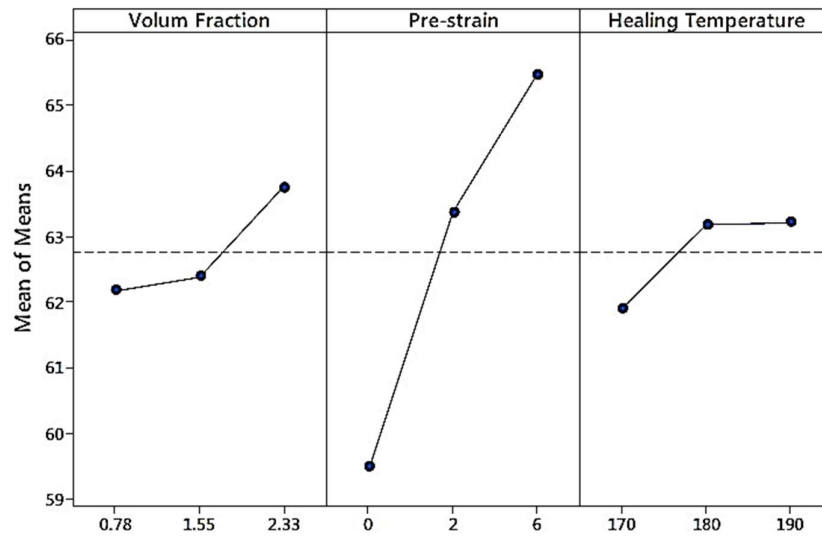


Figure 10. Means plot for the effect of chosen parameters on UTS healing efficiency.

Table 4. Signal to noise result for UTS healing efficiency.

Level	Volume fraction	Pre-strain	Healing temperature
1	35.86	35.48	35.82
2	35.89	36.04	36.00
3	36.09	36.32	36.02
Difference	0.23	0.84	0.19
Rank	2	1	3

As shown in Figure 10, by increasing pre-strain of the strips from 0 to 2 and then to 6 percent, average healing efficiency increased from 59.48% to 65.46% and then to 65.46%. The reason of improvement in healing efficiency with raising pre-strain is the fact that applying more pressure on the crack surfaces accelerates the rate of atomic diffusion and helps healing process to accumulate (Salowitz et al., 2018). Zhu et al. (Zhu et al., 2016) studied this phenomenon using a pre-cracked self-healing metal matrix composite reinforced by SMA wires and showed that employing stress and strain-free wires in composite before loading

cannot close the crack completely. So using pre-strained SMA wires can significantly improve healing capacity.

Figure 10 also demonstrates that increasing volume fraction of the SMA strips continuously increase healing efficiency. By increasing the volume fraction of reinforcement from 0.78% to 1.55% and then to 2.33%, average healing efficiency also grows from 62.18% to 62.39% and then to 63.75%. This result comes from a logical expectation that increasing volume fraction of the SMA strips provides higher pressure force per unit of cross-section area and this force accelerates healing by closing crack surfaces more effectively, allowing the liquid healing agent to flow through the crack due to capillary force. Although the rate of healing efficiency growth for different levels of volume fraction was not as high as pre-strain, it showed a considerable influence on results. Manuel (Manuel, 2007) showed that a minimum of 1% SMA reinforcement is required to ensure healing in an Sn-13 wt.% Bi matrix alloy and she pointed out that using high volume fractions of SMA reinforcement have experimental difficulties and in some cases are impractical.

According to Table 4 and Figure 10, the healing temperature had the lowest impact on UTS healing efficiency. By increasing healing temperature from 170 °C to 180 °C and then to 190 °C average healing efficiency increased from 61.91% to 63.19% and then to 63.22%. Even though increasing temperature creates a higher liquid fraction in the matrix alloy and provides more healing agent, improvement in healing efficiency from 180 °C to 190 °C was not noticeable. Manuel (Manuel, 2007) also reported that a healing temperature that can provide 15 to 20 percent of the liquid fraction is essential for healing to be accomplished. Some researcher like Ferguson (Ferguson et al., 2015) used a healing temperature near liquidus temperature assisting a sand mold to solve specimen's structural stability problem. So it can be concluded that although higher healing temperatures help to heal by providing more liquid

healing agent, since structural stability is a key factor in healing procedure, using a cast as holder would be necessary to preserve original shape of the specimen.

3-2- Ductility

Table 5 presents the amount of ductility before healing, after healing and healing efficiency which was calculated for all of the specimens. The overall means of all nine specimen's ductility before and after heal was 3.94 MJ/m^3 and 2.84 MJ/m^3 , respectively. Also, an average ductility healing efficiency of 72.06% was achieved in which the highest healing efficiency was 87.28% from specimen 1, and lowest healing efficiency was 55.22% from specimen 8.

Table 5. Experimental results of ductility.

Specimen No.	Ductility before healing (MJ/m^3)	Ductility after healing (MJ/m^3)	Healing efficiency (%)
1	4.09	3.57	87.28
2	2.54	1.67	65.75
3	4.01	3.22	80.30
4	3.99	3.06	75.94
5	4.45	3.03	68.10
6	4.10	2.92	71.22
7	3.68	2.73	74.18
8	4.69	2.59	55.22
9	3.91	2.76	70.59

These experimental results were also analyzed using Minitab with DOE module by Taguchi. Outcome data which include mean effect plot and signal to noise ratio is shown in Figure 11 and Table 6, respectively. According to Table 6, pre-strain is still the most critical

factor that makes an influence on healing efficiency. Volume fraction and healing temperature are the next important factors, respectively.

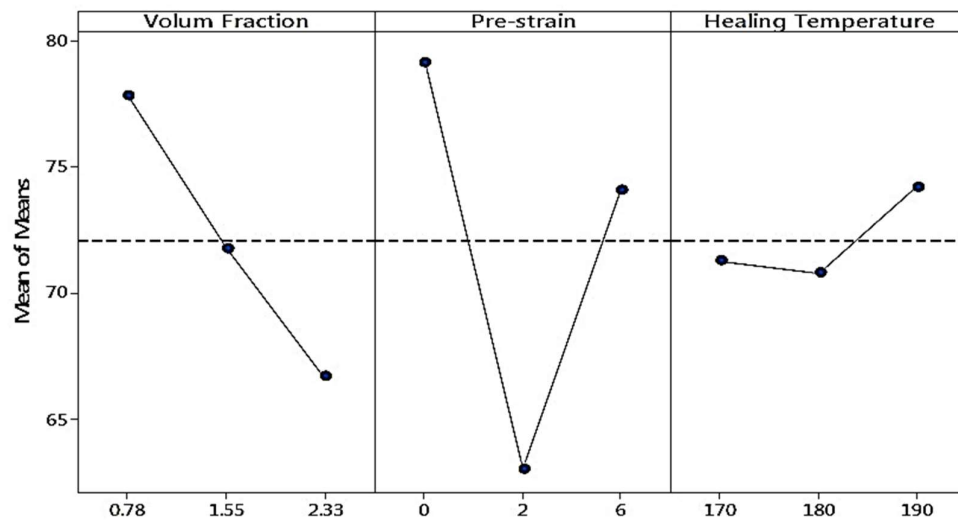


Figure 11. Means plot for the effect of chosen parameters on ductility healing efficiency.

Table 6. Signal to noise result for ductility healing efficiency.

Level	Volume fraction	Pre-strain	Healing temperature
1	37.76	37.94	36.90
2	37.11	35.95	36.98
3	36.41	37.37	37.39
Difference	1.35	1.99	0.48
Rank	2	1	3

As shown in Figure 11, increasing pre-strain from 0 to 2 percent, average ductility healing efficiency decreased from 79.13% to 63.02%, but increasing pre-strain from 2 to 6 percent increased healing efficiency from 63.02% to 74.04%. Since increasing pre-strain, provides higher compressive force during the healing process, it is expected to see amplification of the healing efficiency by increasing pre-strain. But increasing pre-strain also have destructive

effects on the strength of the matrix-strip interface (Khalili and Saeedi, 2017). Reduction in the matrix-strip interface strength would weaken the load transferring ability. This effect would result in the reduction of transferred force that leads to decreasing healing efficiency.

On the other hand, the growth of volume fraction from 0.78% to 1.55% and then to 2.33% continuously lessened the average ductility healing efficiency from 77.78% to 71.75% and then to 66.66%. The reason for this reduction can be the formation of discontinuities within the matrix due to placing SMA strips close to each other. Another possible reason for the reduction in ductility as pointed out by Rohatgi (Rohatgi, 2014) and Manuel (Manuel and Olson, 2007) can be the formation of a layer of oxide on crack surfaces immediately after exposure to air.

Healing temperature amplification from 170 °C to 180 °C did not affect ductility healing efficiency significantly, and efficiency changed from 71.24% to 70.76%. But more increase in healing temperature from 180 °C to 190 °C enhanced the ductility healing efficiency from 70.76% to 74.19%. Since the liquid fraction of the matrix alloy at 190 °C is much higher, this temperature has substantial influence in reorganization and elimination of structural deficiencies, and so 190 °C would be the optimal temperature to ensure robust healing.

4- Conclusion

In the current study, the effect of different fabrication and healing parameters in various levels on healing efficiency were investigated experimentally by using the Taguchi method. SMA Strips volume fraction, pre-strain and healing temperature were studied each in 3 different level. Shape memory alloy strips were embedded within an Sn-Bi matrix alloy (with 13 wt.% of Bi) using casting fabrication procedure. Specimens were tensile tested before and after healing, and by using tensile test data, healing efficiency of every specimen for each mechanical property was calculated.

- Data analysis by Taguchi method showed that 2.33% SMA volume fraction, 6% pre-strain in strips and a healing temperature of 190 °C are the optimal overall circumstances to maximize ultimate tensile strength healing efficiency.
- Ductility healing efficiency also can be optimized by using 0.78% of SMA reinforcement, 0% pre-strain and 190 °C healing temperature that are the optimal levels of each involved parameter to accumulate ductility healing efficiency.
- Amplification of the volume fraction of the SMA reinforcement increases the UTS healing efficiency but at the same time decreases the ductility healing efficiency. Raising the healing temperature always enlarges the healing efficiency for both UTS and ductility. Although increasing pre-strain, increases UTS healing efficiency, it does not have a predictable influence on the ductility healing efficiency.
- Increasing volume fraction even more than 2.33% creates serious fabrication difficulties and affects the internal structure of the specimens due to compaction of the strips. Also, SMA strips cannot tolerate higher pre-strains and raise healing temperature would make the specimen's structure unstable.

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