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A Study on Actuation Performance of Nickel-Titanium Shape Memory Alloy Woven Fabrics (Ni-Ti SMA WFs) with Different Woven Structures

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Nickel-Titanium Shape Memory Alloy (Ni-Ti SMA) wire is one of the popular shape memory materials that has been used in various textile applications due to their ability to deform and return to original state upon exposing to an external stimulus such as temperature, light, chemicals, pH and a magnetic field. Today's, the integration of shape memory materials in textile can be seen in a form of yarn, fabric and clothing. In addition, it is very important to make sure that the main characteristics of the material are able to work well in textile substrate without any disruption from the textile structures. Therefore, the present study explores the actuation performance of a thin Ni-Ti SMA wire weave in three different constructions which were plain, twill 3/2 and satin 4/1. The actuation time (s) from the front and back faces of the Ni-Ti SMA WFs were compared. As a result of the study, the plain structure demonstrated a faster actuation performance at back face at 49 seconds, 28 seconds and 17 seconds in comparison with the twill 3/2 and satin 4/1 structures at both front and back faces due to the more surface contact of the wire on the fabric to the heater.

Keywords: Shape Memory Alloys (SMAs); actuation performance; woven structure; Ni-Ti SMA WF

I. INTRODUCTION

Smart Textile is becoming popular in the textile industry. A combination of an electrical and/or electronic component, chemical stimulate materials and smart materials establish a new textile material called the Smart Textile. Smart Textile can be classified into two different categories; that uses technology for fashion and design purpose, and performance enhancing that assist in human function (Bhatia, 2016). In fact, its ability to detect and react to an external effect change such as light, heat, pressure, electromagnetic waves, sound and ultrasonic waves, motion etc. is quite impressive (Yüce, 2017).

Nickel-Titanium Shape Memory Alloy (Ni-Ti SMA) is one of the examples of advanced and smart material. In comparison with other metals, Ni-Ti SMA can deform to its original shape upon changes in thermal, mechanical, magnetic or electric properties exerted on it (Ahmad *et al.*, 2013). Shape memory alloys are metals that promote either two unique properties which are the superelastic effect (SE) or shape memory effect (SME) (Winchester & Stylios, 2003; Lomov *et al.*, 2015). The Ni-Ti SMA SE refers to the ability of the metals to react to the changes of the molecular structure upon large recoverable strains. Meanwhile, the Ni-Ti SMA SME is specified according to the capability of a material to change shape upon temperature changes in which the material will deform or return into its pre-deformed shape (Göka *et al.*, 2015).

On the other hand, there are many ways to incorporate electrical or smart functional materials into the textile

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substrate. For instance, it can be done by coating, laminating, encapsulating, or embedding through knitting or weaving. Among others, the weaving technique is the most suitable way to produce flexible and foldable textile materials which are then beneficial for the Ni-Ti SMA. With reference to the previous work, in order to make the smart materials to work (Göka *et al.*, 2015). The smart materials are complex materials; however, they are unique and impressive due to their ability to process, analyse and respond. What make them even more amazing is they can adapt and respond to the environment. They possess full ability to change themselves by responding to the external factors such as temperature, pressure and density or even internal energy (Syduzzaman *et al.*, 2015).

Weaving is an interlacement of warp and weft yarn. The output of the weaving process is called woven fabric. The interlacement of both yarns produces a structure of woven fabrics in terms of fabric compactness in comparison with knitted fabrics. Unique patterns can be produced by allowing the weft yarns to skip several warp yarns before interlacing. Three main fabric structures for the construction of woven fabric are named plain weave, twill 3/2 weave, and satin 4/1 weave. A plain weave is formed by each warp yarn which passed alternately under and over each weft yarn and tends to have higher strength. Twill 3/2 weave instead, has warp yarns weaved over and under two or more weft yarns at one time, which giving a diagonal pattern of a fabric that is smoother to touch. In a satin 4/1 weave, the warp yarns passed over four or even more weft yarns before weaving it under one warp yarn, thus giving it a very tight weave, an even surface and having lustre on one side (Buckner & Rebecca, 2018).

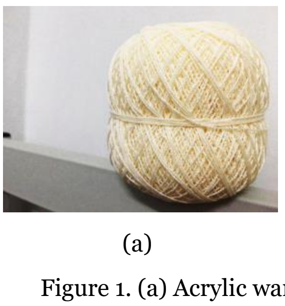
Those structures performed a different yarn's float on the resultant woven fabric. Moreover, the yarn's floats are related to yarn crimp number in the woven fabric structure. Due to the higher crimp value of the yarns, there is a higher restriction of yarn movement in the fabric structure. In fact, fabric crimp also determines the extensibility of the fabric. Generally, a plain weave fabric has the highest crimp because of its maximum intersection points compared to the other two basic structures which are twill 3/2 and satin 4/1 weaves (Kumar & Hu, 2018).

Therefore, this study aims at showing the weaving of the Ni-Ti SMA in a form of thin wire into the specific weave structures; plain, twill 3/2 and satin 4/1. The interlacement between the Ni-Ti SMA wire and the warp and weft yarns in the woven fabric structures are expected to restrict the actuation performance upon heating. The actuation performance was determined through a heat conduction method and was reported in the time of actuation in second (s). The condition of the resultant Ni-Ti SMA woven fabrics was observed and discussed.

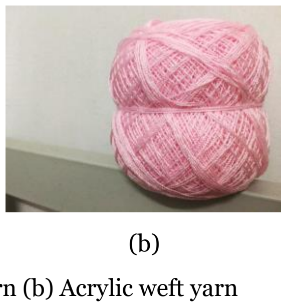
II. MATERIALS AND METHOD

Weaving is a process of producing woven fabric by interlacing two types of yarns which were warp and weft yarns at 90 degrees crossover point (Kumar & Hu, 2018). In this experiment, the selected yarns for warp and weft were white acrylic and pink acrylic (as shown in Figure 1(a) and 1(b)). The FLEXINOL Ni-Ti SMA wire, which was supplied by Dynalloy Inc., was 0.012inch in diameter, in a straight annealed condition and was set at an austenite temperature which was 70°C (as shown in Figure 2).

The samples of Ni-Ti SMA WFs were produced in three different woven structures which were plain weave, twill 3/2 weave, and satin 4/1 weave by using an 8-shaft table loom. Basically, there were three important mechanisms in the weaving process which were shedding, picking and beating. Shedding is a process of separating the warp yarns into two layers to form a tunnel known as shed by raising or lowering the heald shafts on the loom. Meanwhile picking is a process of inserting the weft yarn through the shed by using a shuttle or any shuttleless mechanism. Beating is the next process after picking which is to push the newly inserted weft yarn to the fabric fell with the assistant of reed. Above all, shedding is the most crucial part in producing the different types of woven structures where each type of the woven structure requires a different set up of the draw-in on the loom. Additionally, the size of the woven fabric samples was set approximately at 3.35inches X 3.35inches. Figure 3 and 4 show the 8-shaft table loom and illustration of the important mechanisms in the weaving process respectively.



(a)



(b)

Figure 1. (a) Acrylic warp yarn (b) Acrylic weft yarn

Figure 2. Ni-Ti SMA wire

Figure 3. 8-shaft table loom
(Kadolph, & Marcketti, 2014)

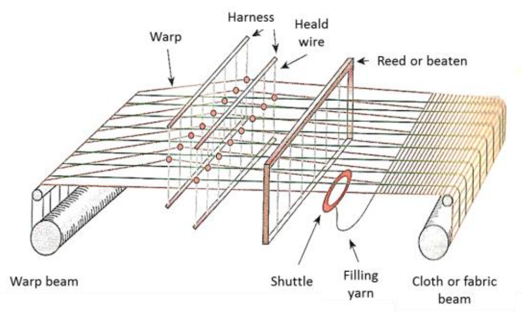


Figure 4. Important mechanisms in the weaving process
(Kadolphv& Marcketti, 2014)

The first step for the preparation of any woven fabric sample is a drawing-in. In this experiment, the drawing-in process was done to set up the warp yarns from a beam, then move through heald eyes on the heald shaft and finally, pass through the dents on the reed. The warp yarns were set up according to the required woven structures. A straight draft arrangement of the heald shafts was applied to weave the woven fabric samples.

For plain weave, only two heald shafts were used. The drawing-in of the first warp yarn was on the heald eye number 1 of the heald shaft number 1, and the second warp yarn was inserted through the heald eye number 1 of the second heald shaft. Then, the warp yarn number 3 was inserted through the heald eye number 2 of the heald shaft number 1 and the warp yarn number 4 was inserted through the heald eye number 2 of the second heald shaft. The drawing-in of the end was alternately continued until the 61-end.

Then, for twill 3/2 weave and satin 4/1 weave, the drawing-in of the warp yarns involved only five heald shafts. The warp yarns number 1, 2, 3, 4 and 5 were inserted through heald eyes number 1 of the heald shafts number 1, 2, 3, 4 and 5. Then, the warp yarns were alternately inserted through the next heald eyes of the heald shafts until the 61-end. The width of woven fabric samples was 3.35 inches which required only 61-end.

After the drawing-in process completed, the warp yarns were tied up on the warp beam and the take-up roller to ensure that the tension of warp yarns were consistent along the weaving process. Next, the weft yarn or pick was wound onto the wooden shuttle. The Ni-Ti SMA wires were then cut into 4.33inches each and were inserted alternately through the opening of the shed of the woven fabric. Nine pieces of the individual wire were weaved into the fabric structure. As for the woven structure a sample, the shedding was operated according to the lifting plan of the different woven structures. After that, picking took place as to insert the weft yarn through the shed by using the shuttle. The first step of producing samples was to push the newly inserted weft by the reed to the fell of the cloth. Then, the pick insertion was repeated until the length of the samples were at approximately 0.55inch. As for the next pick, one Ni-Ti SMA wire was inserted through the shed. After that, the weft yarn was again inserted. The gap between the SMA wires was 0.2inch. Next, the pick was alternately continued until the third SMA wires were inserted. After the first phase of the samples was completed, the picking was continuously repeated two times to get three phases of the woven structure's samples. Finally, the picks were repeated until the length of the ninth Ni-Ti SMA wire to the last pick was at approximately 0.55inch. The last step was to withdraw the woven structure samples from the take-up roller. Figure 5 shows the insertion of weft yarn through the opening of the shed. Figure 6 shows the specific woven structures used in the weaving process.

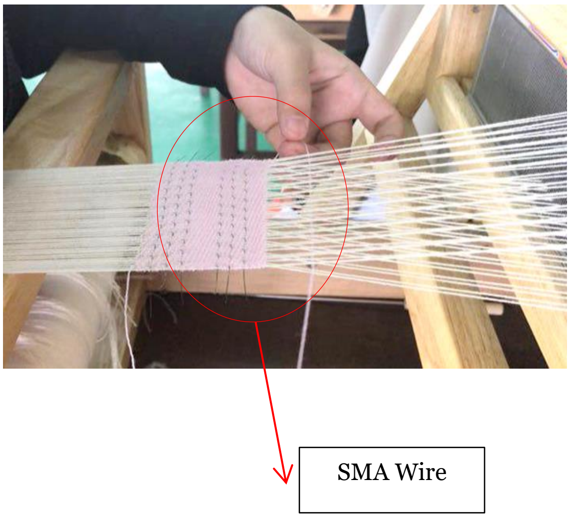
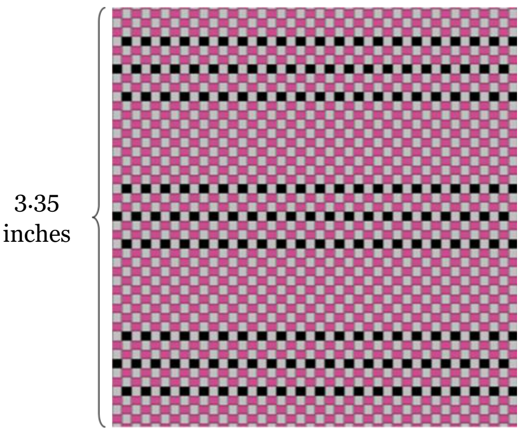
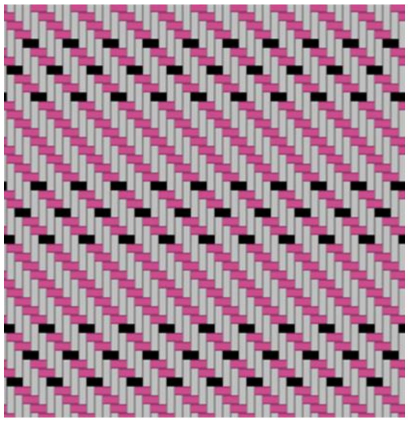


Figure 5. The insertion of SMA wire and weft yarn in weaving process



(a)



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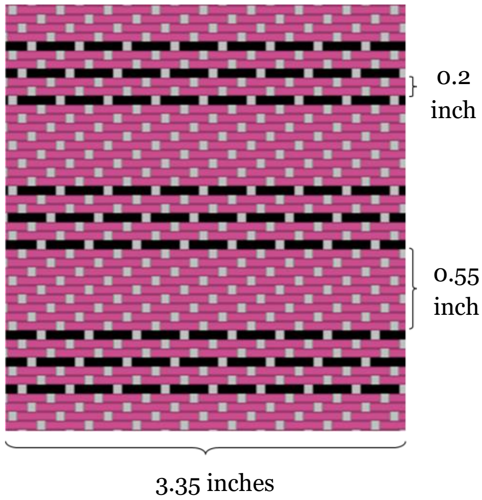


(c)

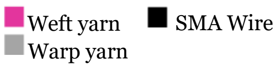


Figure 6. Woven structures; (a) Plain, (b) Twill 3/2 and (c) Satin 4/1

1. *Physical test*

The densities of the Ni-Ti SMA WFs were tested by using the Folding Pocket Magnifier. The density of this fabric was determined by the number of warps and wefts per inch or per inch. A folding pocket magnifier was used to count the number of warp and weft yarns in an $inch^2$ of fabric.

The counting for fabric density can be done in five samples but the yarn should not be counted twice. Meanwhile, the thickness of the fabric was measured by using a digital thickness gauge. The thickness of the fabric was determined in inch. Several readings were taken from the sample and the result was averaged.

2. Actuation test

The test was conducted by using a heat conduction method. The specific test set-up was prepared in the lab and accompanied by a hot plate, retort stand, stopwatches, and video camera. The hot plate was used as a heating source for the woven fabrics, while the rest were used to assist the recording of the time of actuation of the woven fabrics. The hot plate was set at 150°C and in constant 26°C of a room temperature. The actuation test set-up was placed on a clean table in order to make a clear observation of the actuation test. Three sizes of polyvinylchloride (PVC) molds which were 0.79inch, 1inch and 1.26inches, were used to replicate the folding condition of the woven fabrics before they were exerted on the hot plate (see Figure 7). The digital camera and stopwatch started to record right after the samples were placed on the hot plate and stopped immediately after the actuation ended. The digital camera was used to record the actuation time and shape recovery formation of the samples. Times taken to recover the Ni-Ti SMA WF to its original shapes were indicated depends on their weave structures. The time of the molded woven fabrics expanded and recovered into the original shape was recorded by four observers with a stopwatch and their condition during the actuation was observed and discussed. Four people were required to observe and at the same time record the actuation time (Ahmad *et al.*, 2013). The fabric samples were tested for their front and back faces. Five readings of both front and back faces were taken for each fabric sample. The front face of each sample was taken first to allow it to rest before the test was continued with the back face and one reading was completed. This test was replicated and modified in accordance with the previously reported work (Ahmad *et al.*, 2013, Chenal *et al.*, 2014). Figure 8 and 9 show the schematic test set-up in the 3D isometric and top view respectively.

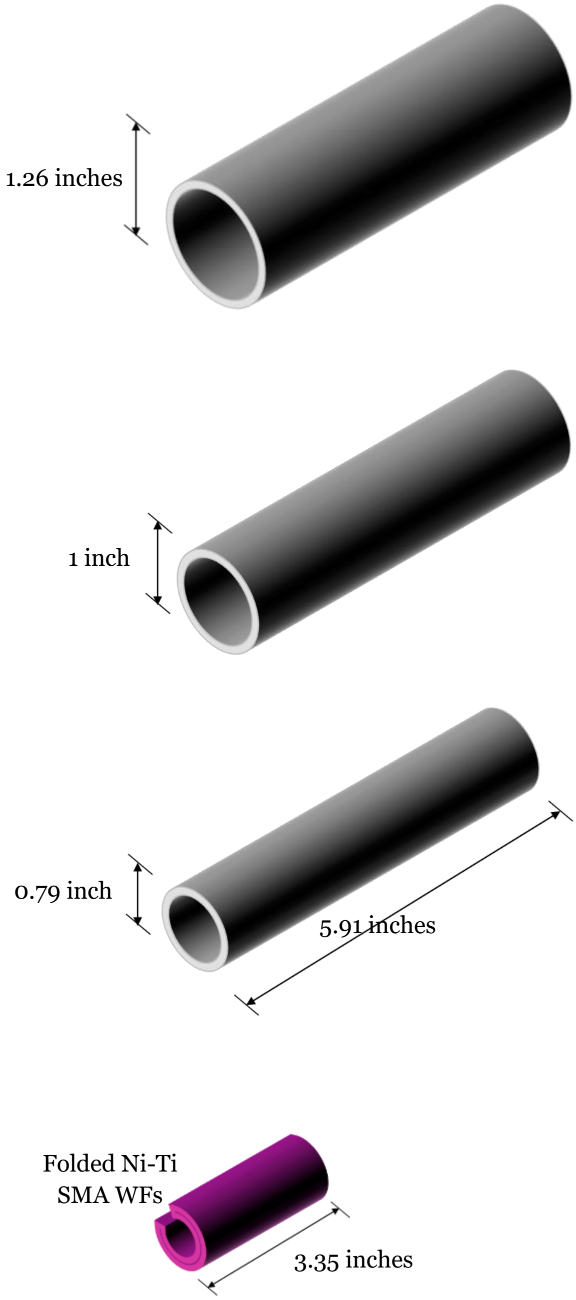


Figure 7. PVC molds to replicate the consistence folding condition

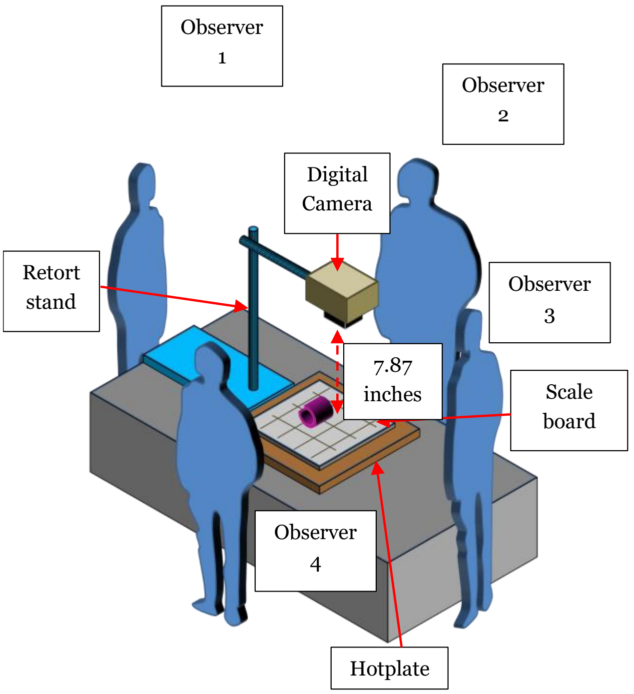


Figure 8. Schematic test set up drawing from the 3D isometric view

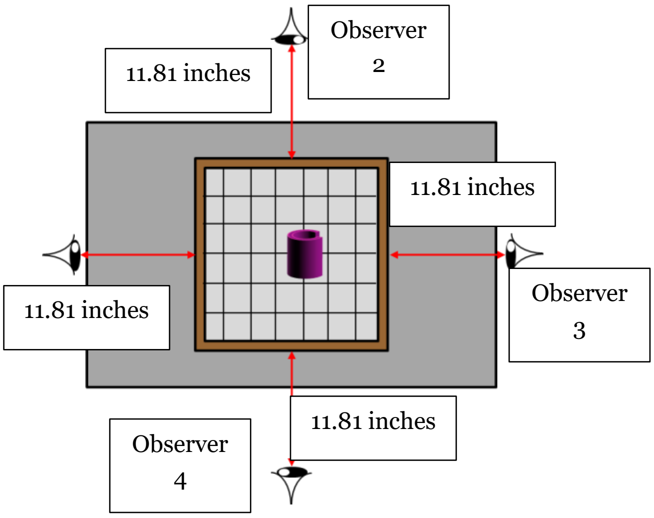
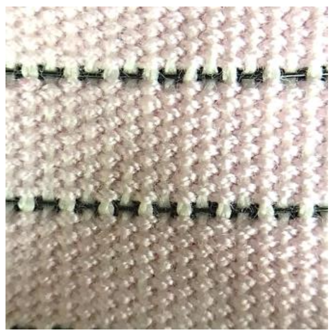


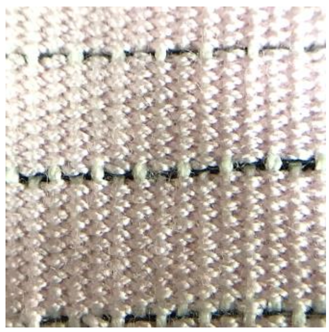
Figure 9. Observation method schematic drawing from the top view

III. RESULT AND DISCUSSION

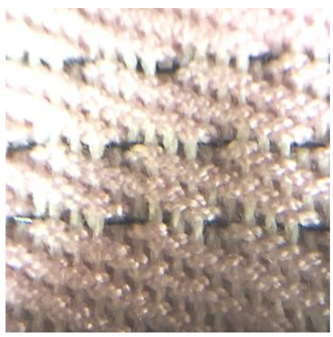
The structures of Ni-Ti SMA woven fabrics for both front and back faces were shown in Figure 10 (a) – 10 (c). The black vertical line in the weft direction on the fabric was the wire. From the picture, it shows that the wire was unclearly exposed for the twill 3/2 and satin 4/1 structures at their front face. However, the wire was unseen for the back face of the satin 4/1 structure. The high numbers of floats of the satin 4/1 structure create a bulkiness effect on the fabric and caused the wire to be slightly hidden behind the yarns. The plain structure fabric felt more rigid in comparison with the satin 4/1 structure. This was probably due to the number of interlacements between the wire and the warp and weft yarns. The plain structure consisted of more yarn's interlacement between warp and weft yarns in comparison with the satin 4/1 structure. As a result, the yarn was held to each other tightly in the fabric structure than the satin 4/1 structure where it was too loose. For all the samples, the fabric in the weft direction felt more rigid during bending than in warp direction because of the wire. Meanwhile, the twill 3/2 structure possessed a balanced feeling and the front and back faces of the fabric looked the same as the plain structure but slightly softer.



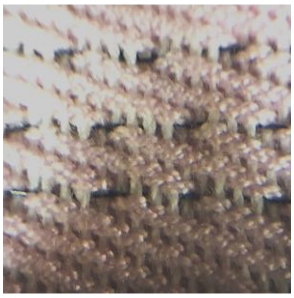
(a) Front face



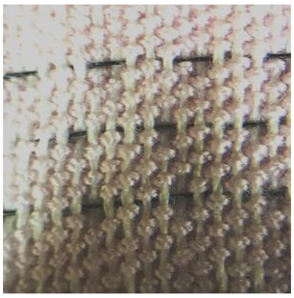
(a) Back face



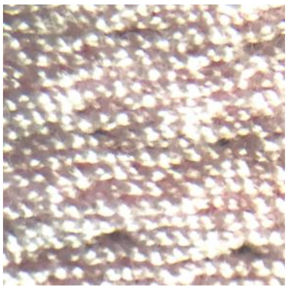
(b) Front face



(b) Back face



(c) Front face



(c) Back face

Figure 10. The structures of the Ni-Ti SMA woven fabrics; (a) plain (b) twill 3/2 (c) satin 4/1

A. Physical Testing

Two physical testing were conducted namely density and thickness. All data were interpreted in Table 1. Table 1 shows the amounts of warp per inch for all the samples were approximately half of the weft per inch. This was due to the existence of wire in the woven structure where it was finer in size than the yarn. In addition, the fine size of wire tended to create the gap between the warp yarns and cause some loose handling in the warp direction. Besides, the thickness increased occurs due to the changes of plain to satin 4/1 structure. The more thickness the fabric, the more bulkiness the handling effect of the woven fabric. The increment thickness value was probably caused by the increment number of floats on the woven fabric structures. The satin 4/1 structure possessed the highest number of floats than the twill 3/2 and plain structures.

Table 1. Physical testing result

Structures	Density		Thickness (inch)
	Warp/inch	Weft/inch	
Plain	18	36	0.046
Twill 3/2	19	39	0.065
Satin 4/1	18	39	0.078

B. Actuation Test

Figure 11 – Figure 13 illustrate the time of actuation of the Ni-Ti SMA WF with three different weave structures and folded size. In Figure 11 - Figure 13, it can be seen that the time of actuation of the Ni-Ti SMA WF slightly increased from plain to satin 4/1 structures either at front face or back face. Moreover, the back face of the plain structure demonstrated a faster actuation time at 49 seconds, 28 seconds and 17 seconds in comparison with the front and back faces of the twill 3/2 and satin 4/1 structures at all folding conditions. The results also show that the plain structure was able to return into its original shape very fast although it was given the extreme folding condition which was at 0.79inch size. This situation was probably due to the surface contact of the wire on the fabric to the heater whereby, for the plain structure, most of the wires appeared clearly on the fabric surface and were directly exposed to the heater. While for the twill 3/2 structure, the wire was slightly hidden and as for the satin 4/1 structure, the wire was completely hidden. Both situations were due to the floating yarns. The heat took a short time to be transferred to the wire surface as fewer warp yarns covered the SMA wire. The more warp yarns covered the wire, the more time it took to transfer the heat to the wire surface as they had to pass through the warp yarns before heat the wire. Moreover, the higher the folding condition size which was from 0.79inch to 1.26inches, the shorter actuation time that took place for all the woven structures. This was probably because of the restriction that occurred in the wire movement of the fabric structure during the actuation. When less restriction was given to the wire which was due to the increase size of the mold, then cause faster recovery into

the original shape. In another point of view is the satin 4/1 structure could have a faster actuation at its back face due to the high number of floats of wires in comparison with its front face. However, it did not happen as expected as it was probably due to the bulkiness of the handling effect (as stated previously) on the back face of the satin 4/1 fabric structure and tended to cover most of the floating wires that should appear clearly at the back face. Since the wires were completely covered by the yarns, the wires were not able to absorb the heat immediately and caused a longer time to actuate, hence take a longer time being on the hot plate until the actuation process is completed.

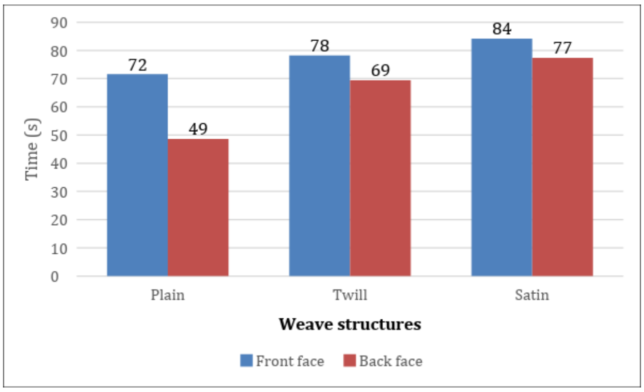


Figure 11. The actuation performance of the Ni-Ti SMA WF with different structures at 0.79inch folded size

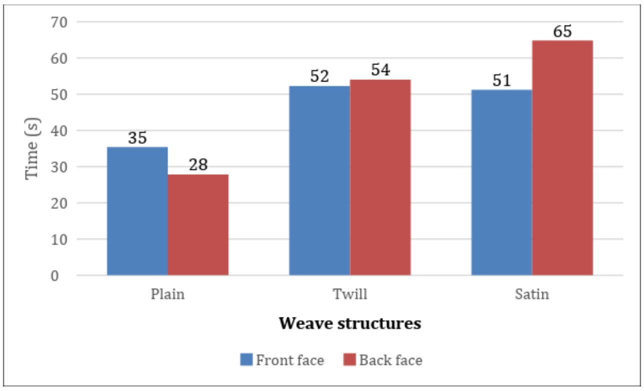


Figure 12. The actuation performance of the Ni-Ti SMA WF with different structures at 1inch folded size

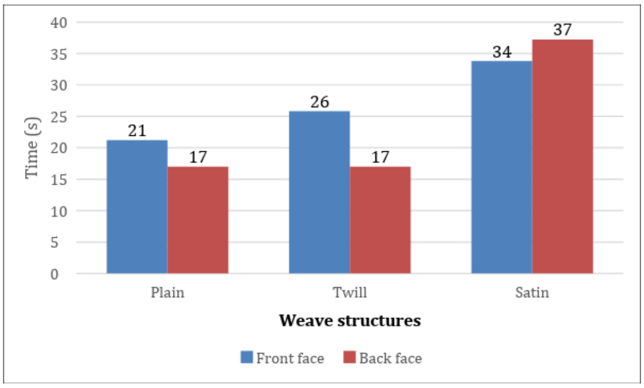


Figure 13. The actuation performance of the Ni-Ti SMA WF with different structures at 1.26inches folded size

IV. CONCLUSION

The Ni-Ti SMA actuator wire was successfully weaved with three different woven structures; plain, twill 3/2 and satin 4/1. The plain structure was more rigid than the twill 3/2 and satin 4/1 structures due to the high number of interlacements between warp and weft in the plain structure fabric. The number of wefts per inch was half greater than the warp per inch due to the existence of wires in the weft direction where it was finer in size than the yarn size. The presence of the fine size wire in the woven structure create the gap between the warp yarns and cause some loose handling in the warp direction.

For the actuation performance test, the plain structure demonstrated a faster actuation performance at back face at 49 seconds, 28 seconds and 17 seconds in comparison with the twill 3/2 and satin 4/1 structures at both front and back faces due to the surface contact of the wire on the fabric to the heater. Besides, the satin 4/1 structure have a lowest actuation time at its back face 77 seconds, 65 seconds and 37 seconds as expected earlier. This condition is due to the bulkiness of the handling effect on the back face of the satin 4/1 fabric structure and tended to cover most of the floating wires that should appear clearly at the back face.

V. ACKNOWLEDGEMENT

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