Influence of Pre-strain on the Strain Rate Response of Ni-Ti Shape Memory Alloy

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ABSTRACT

The presence of Shape Memory Alloy (SMA) in civil engineering fields offered a lot of advantages to the industries. The superiority of SMA is when the material has the ability to remember its previous shape after it has deformed and it will return back to its original defined shape when it is subjected to heat. Nickel-Titanium (Ni-Ti) is known as the finest alloy among SMA groups. In this research, the influence of pre-strain on the mechanical behavior of Ni-Ti shape memory alloy bars were examined in room temperature with concerns of a different strain rates, which are $5.5x10^{-4}\ s^{-1}$ *and* $1x10^{-3}\ s^{-1}$*. Each of the test piece was pre-strained at level* 5ξ, 10ξ *and* 15ξ*. A quasi-static tensile test was carried out on heat treated Ni-Ti by using a Universal Testing Machine to observe the Ni-Ti stress-strain response. The results show tensile strength of Ni-Ti increased after applying pre-strain and heat treatment at 500°C. However, it is observed tensile strength of Ni-Ti started to drop after pre-strained at* 15ξ*. So, it indicates that strain ageing of Ni-Ti bars at a large strain becomes practically irrelevant, even though Ni-Ti is a super-alloy. Furthermore, Ni-Ti is a strain rate dependent material where the strength increases at a higher rate. Thus, it was found Ni-Ti exhibited yield strength differently where the yield strength increases as the strain rate decreases.*

Keywords: *Ni-Ti, Shape memory alloy, Pre-strain, Strain rate, Tensile*

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Introduction

The implementation of shape memory alloy (SMA) in structural applications can be considered as new and still under research. Researchers realized the specialties of SMA can be a great factor to develop better technology in the construction field. SMA is recognized to have the ability to remember its original state and able to recover back to the previous shape after being deformed with the aid of heat [1]–[5].

More than thirty different types of SMAs was recorded, but only three are widely known such as Nickel Titanium (Ni-Ti), Copper Zinc Aluminium (Cu-Zn-Al) and Copper Aluminium Nickel (Cu-Al-Ni) [4]. These SMAs are well known in applications of medicine, dentistry, robotic and also in consumer goods.

Ageing studies on strain have been conducted on steel as it can make the metal apparently becomes stronger and more difficult to deform. Therefore, in order to use SMA on concrete structures, studies on strain is suitable to be conducted on SMA where it needs to be strong enough to cater the load acted upon it. By understanding the strain rate of a material will ensure that it meets the performance specification required in the end use for the application. Thus, it can predict the behavior of a particular material during processing operations and service periods. Furthermore, the ageing mechanism can provide a better control and development of this alloy for engineering applications.

In general, strength properties for most material tend to increase at higher rates of deformation. Noradila et al, [6] studied the effect of strain rate on Al-Zn magnesium alloys and they found tensile strength of Al-Zn magnesium alloy was strain rate dependent where tensile strength increases with increasing strain rate. Tobushi et al [7] used Ni-Ti wires to determine the influence of strain rate and the result shows the higher the strain rate, the larger the dissipated work density. Wang et al, [8] explored the improvement of shape memory effect after pre-deformation and they found the shape recovery effect can be improved through ageing after pre-deformation. Most of the research focused on the wire types of SMA. Little information is known about the SMA bar behavior. In consideration of the SMA used for structural purposes, the larger capacity of SMA is more fitted the conditions. Thus, the stress-strain behavior of SMA bar is investigated in this study.

Experimental Work

Materials

This study used Ni-Ti types of SMA as the main material to undergo the experimental procedure. It is proven that among SMA group, Ni-Ti is the best type of SMA[2]. For this study, Ni-Ti is supplied by SAES Smart Material Inc, USA. The tests were carried out on a bar type specimen of 8 mm diameter and the length of the specimen was chosen to be 400 mm as shown in Figure 1. The size of the specimen is chosen due to the capacity limit of the tensile test machine available in the laboratory.


Figure 1: A 400 mm of Ni-Ti bar.

Pre-strain

The effects of different pre-strain levels were investigated on the Ni-Ti through the monotonic tensile test. The specimens are first subjected to pre-strain at the level of 5ξ, 10ξ and 15ξ. A study by Momtahan et al., [9] said that the structural post-earthquake performance on the effects of strain ageing starts to be a concern when the plastic strain level is moderate which is between 10ξ_y and 15ξ_y, where ξ_y is the yield strain of the reinforcing steel bar. When the level of pre-strain is past 10-15ξ_y, damages occurred are not economically to be repaired, hence strain ageing of reinforcing bars at large strain becomes practically irrelevant. In this study, the pre-strain levels are applied to the Ni-TI bars as 5ξ, 10ξ and 15ξ. The pre-strain level at 15ξ was carried out to ensure the large pre-strain level is within the range of practical interest of Ni-Ti properties. All the specimens used were in good condition as they were delivered to the laboratory for testing

Heat treatment

Heat treatment at 500˚C was applied to the specimen after the pre-strain stages to recover the physical properties of a material or more precisely to increase the surface strength of the Ni-Ti alloy material so that the material is hardened and it will be difficult to cut, shape or bend. Typically for superelastic material, a heat treatment at 500°C range is adequate and the heat treatment time is about 30 minutes. If high temperature imposed to the Ni-Ti, the tensile strength will reduce drastically. The specimen is heated inside the furnace and water quench is recommended to cool off the specimen as cooling should be rapid to avoid ageing from affected on the material properties. The hardening process will be completed after cooling process.

Strain rate

Ni-Ti specimens were subjected to the conventional quasi-static tensile test after pre-strain and heat treatment stage. Different strain rates were used on the test which are $5.5x10^{-4}$ s^{-1} and $1x10^{-3}$ s^{-1}. Universal Testing Machine (UTM) with the capacity of 1000kN was used to carry out a tensile test on the specimen. Calibrated extensometer was attached to the specimen to capture the applied load and the elongation of the bars.

Results and Discussion

Tensile strength properties of as-delivered Ni-Ti

Tensile test of as-delivered Ni-Ti bars were first verified to provide a standard for the following tests. As shown in Table 1**,** it can be observed that in as-delivered condition Ni-Ti bars, at a strain rate $1x10^{-3}$ s^{-1}, the tensile strength is 935.091 MPa with elongation of 79.8 mm. For strain rate at $5.5x10^{-4}$ s^{-1}, the tensile strength is 1133.318 MPa with elongation of 60.2mm. The value of elongation and stress-strain curves as shown in Figure 2. It was proved that the examined material has relatively low plastic properties which is typical for SMA to have low plastic properties but higher strength to withstand the forces acted upon it.

Table 1. Tensile test results for control specimens using two different strain rate.

Strain rate (s^{-1})	**Stress (MPa)**	**Elongation (mm)**
$1x10^{-3}$	935.091	79.8
$5.5x10^{-4}$	1133.318	60.2

Tensile strength properties of pre-strain specimen heat at 500°C

This section will discuss about tensile strength properties of Ni-Ti specimen that has been pre-strain at level of 5ξ, 10ξ and 15ξ using two different strain rate which are $1x10^{-3}$ $s^{-1}$and $5.5x10^{-4}$ s^{-1}. The specimen has been received heat treatment at temperature of 500˚C. The discussion is focused on the correlation of strain rate and pre-strain by concerning on stress-strain studies of Ni-Ti specimens.

Tensile properties of strain rate at $1x10^{-3}s^{-1}$

Table 2 shows the tensile properties of strain rate at $1x10^{-3}s^{-1}$ with different levels of pre-strain. Figure 3 shows the behavior of Ni-Ti alloys at different levels of pre-strain with strain rate at $1x10^{-3}$ s^{-1}.

Table 2: Tensile properties of strain rate at $1x10^{-3}s^{-1}$

Level of Pre-strain	**Stress (MPa)**	**Elongation (mm)**
5ξ	1230.269	51.8
10ξ	949.434	47.7
15ξ	1279.75	63.4

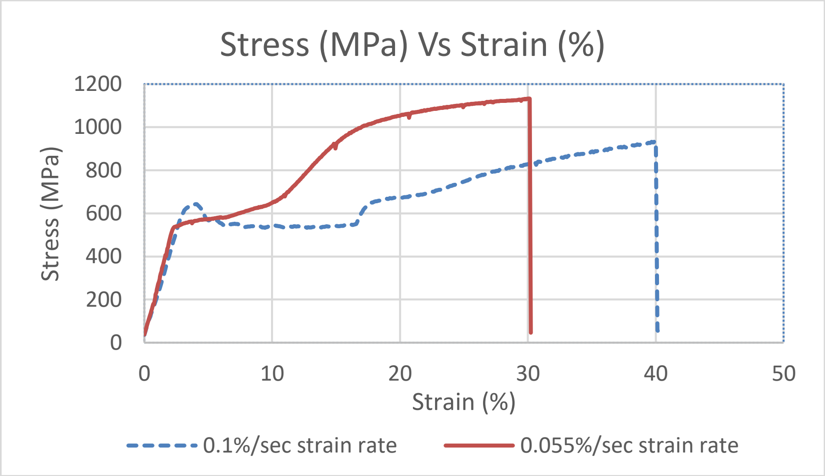

Figure 2: Stress-strain curves relationship for Ni-Ti at different strain rates.

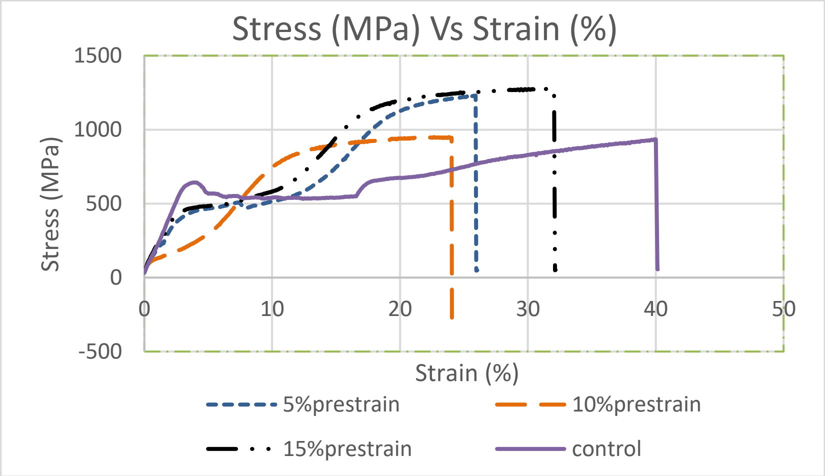

Figure 3: Stress-strain curves at a strain rate of $1x10^{-3}s^{-1}$

Figure 3 shows the stress-strain relationship of the Ni-Ti at a prestrain rate of 1x10^{-3} s^{-1}. From the visual observation, tensile strength of the bars was increased after experienced pre-strain at 5ξ, 10ξ and15ξ where each specimen has higher stress than the control specimen (without pre-strain). The results for pre-strain at 5ξ and 15ξ were quite similar with not much difference in stress. It shows that the stress after pre-strained at 5ξ is 1230.269 MPa and the stress after pre-strained at 15ξ is 1279.75 MPa. This indicates that the stress is increased when the level of pre-strain is higher. Except for the level of pre-strain at 10ξ where the stress is suddenly dropped at 949.434 MPa but still higher than the control specimen.

Tensile properties of strain rate at 5.5x10^{-4} s^{-1}

Table 3 shows the tensile properties of strain rate at 5.5x10^{-4} s^{-1} with different level of pre-strain. Figure 4 shows the behavior of Ni-Ti alloys response to different levels of pre-strain and strain rate at 5.5x10^{-4} s^{-1}.

Table 3. Tensile properties of strain rate at 5.5x10^{-4}s^{-1}

Level of Pre-strain	Stress (MPa)	Elongation (mm)
5ξ	1221.28	51.35
10ξ	1307.15	66.23
15ξ	1265.86	62.59

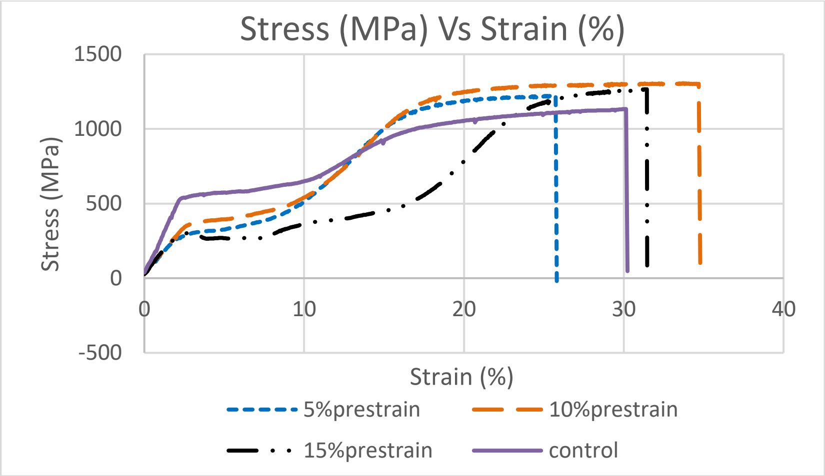

Figure 4: Stress-strain curves at a strain rate of 5.5x10^{-4}s^{-1}.

Figure 4 shows the tensile strength of the Ni-TI bars at a strain rate of $5.5x10^{-4}$ s^{-1} has similar pattern as strain rate at $1.1x10^{-1}s^{-1}$ where tensile strength of each specimen increased after experienced pre-strain at 5ξ, 10ξ and15ξ. The stress after pre-strained at 5ξ is 1221.28 MPa and the stress after pre-strained at 10ξ is 1307.15 MPa, also the stress after pre-strained at 15ξ is 1265.86 MPa. From the visual observation, tensile strength of the bar increased from 5ξ to 10ξ but has decreasing value at 15ξ. According to Momtahan et al, [9], when the level of pre-strain is between 10ξ -15ξ, the damages will occur and it is not economically to repair. Hence, the strain ageing of reinforcing bars at large strain becomes practically irrelevant to be used. Therefore, it is indicates that strain ageing of Ni-Ti bars at a large strain becomes practically irrelevant, even though Ni-Ti is a super-alloy material.

Furthermore, the elongation of the bars as shown in Table 3 also affected by the level of pre-strain. For example, the bars that were tested in strain rate $5.5x10^{-4}$ s^{-1} shows the elongation of the bars is increased from the level of 5ξ to 10ξ, but decreased at level of 15ξ.

Yield strength properties of pre-strained Ni-Ti

Figure 5, Figure 6 and Figure 7 show the relationship between stress vs strain curves at different strain rates after experienced pre-strain at 5ξ, 10ξ and 15ξ for 5%, 10% and 15%, respectively.

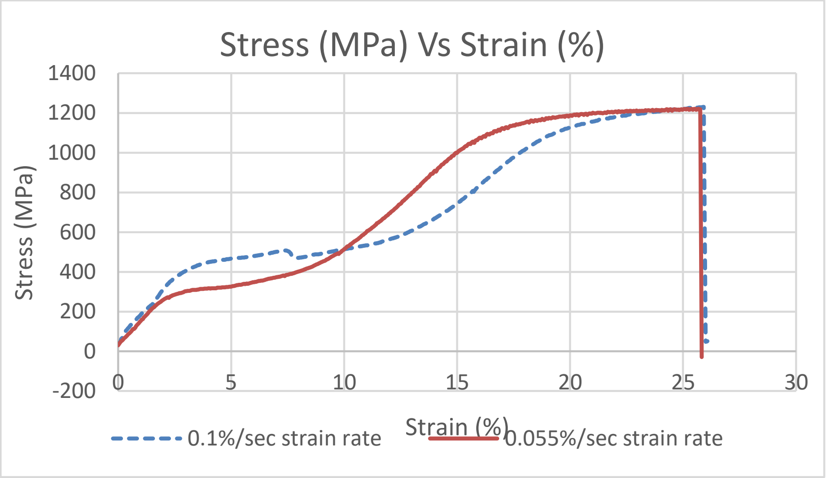

Figure 5: Stress-strain curves at 5% pre-strain with different strain rate

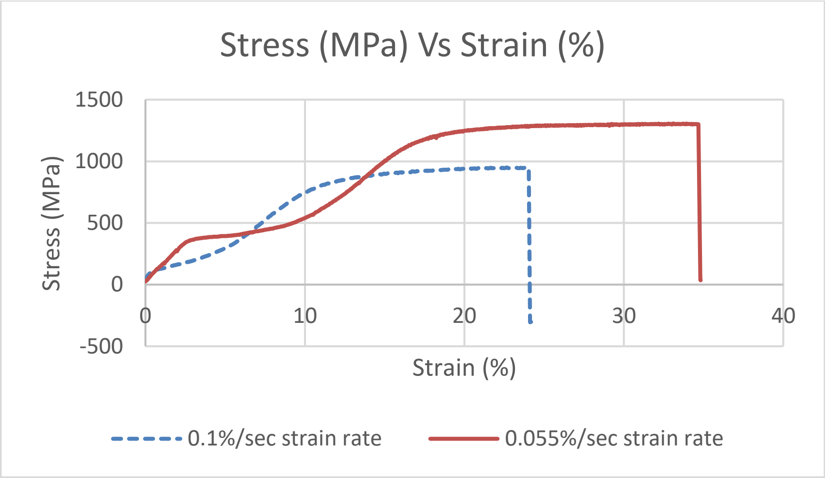

Figure 6: Stress-strain curves at 10% pre-strain with different strain rate

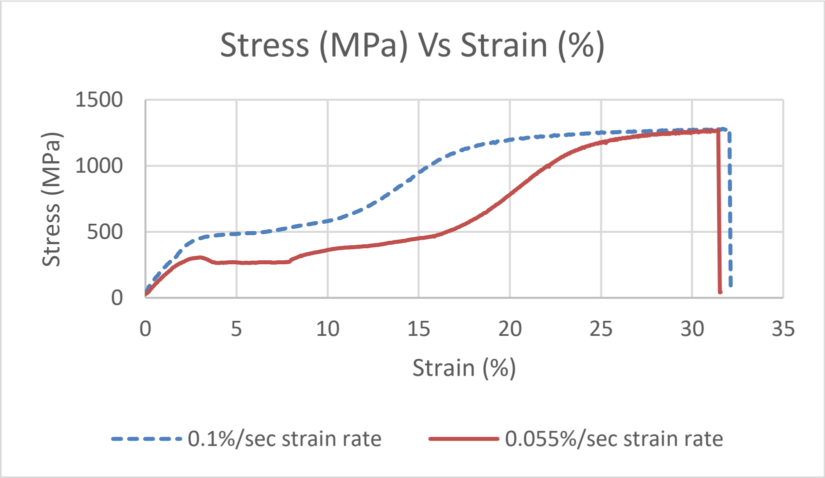

Figure 7: Stress-strain curves at 15% pre-strain with different strain rate

From these graphs, it can be seen that the tensile strength of the Ni-Ti bar which had been tested at strain rate of $1x10^{-3}$ s^{-1} has higher value than a strain rate of $5.5x10^{-4}$ s^{-1}. This pattern can be observed in Figure 5 and Figure 7. According to Davis [10], conventional (quasi-static) tensile test required strain rates between 10^{-5} s^{-1} to 10^{-1} s^{-1} and strength properties of most materials tend to increase at higher rates of deformation.

Table 4: Yield strength results of pre-strained Ni-Ti bar.

Level of pre-strain	**Strain rate (s^{-1})**	**Yield strength (MPa)**
0ξ	$1x10^{-3}$	537.116
	$5.5x10^{-4}$	630.213
5ξ	$1x10^{-3}$	683.118
	$5.5x10^{-4}$	1020.54
10ξ	$1x10^{-3}$	780.057
	$5.5x10^{-4}$	823.49
15ξ	$1x10^{-3}$	662.985
	$5.5x10^{-4}$	996.34

Moreover, Table 4 shows the yield strength for Ni-ti bar is increased after pre-strained at each level. It means that the elastic region for Ni-Ti after pre-strained was greater than Ni-Ti without pre-strained. In general, the yield strength increases with strain rate and decreases with temperature. When it is not the case, the material is said to exhibit yield strength differently, which is typical for super-alloys and leads to their use in applications requiring high strength at high temperatures. It is proved in this study that there is the influence of strain rate on yield strength, where the specimen tested at $5.5x10^{-4}$ s^{-1} has greater yield strength compared to specimen tested at $1x10^{-3}$ s^{-1} at each level of pre-strain.

Conclusion

The influence of pre-strain levels and strain rates on tensile test of Ni-Ti were investigated. From the results obtained, it can be concluded that:

1) Tensile strength of Ni-Ti was increased after applying pre-strain and heat treatment at 500°C.
2) Tensile strength was increased from level of pre-strain at 5ξ to 10ξ and started to drop at level of 15ξ. This explained Ni-Ti bars at strain more than level of 15ξ becomes practically irrelevant and not economically be repaired.
3) Ni-Ti is a strain rate dependent material where the strength was increased at higher rates.
4) Ni-Ti exhibit yield strength differently where the yield strength increases when the strain rate decreases.

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