Structural Engineering and Mechanics, Vol. 22, No. 5 (2006) 563-574
DOI: http://dx.doi.org/10.12989/sem.2006.22.5.563

Unique local deformations of the superelastic SMA rods during stress-relaxation tests

Muhammad Ashiqur Rahman† and Mujibur Rahman Khan‡

Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka 1000, Bangladesh

(Received January 20, 2005, Accepted December 12, 2005)

Abstract. This paper studies mechanical behavior of the superelastic shape memory alloy (SMA) rods in terms of local deformations and time via tensile loading-unloading cycles for both ends fixed end constraints. Besides the unique stress induced martensitic transformation (SIMT), SMA's time dependent behavior when it is in mixed-phase condition upon loading and unloading, also need careful attention with a view of investigating the local deformation of the structural elements made of the same material. With this perspective, the so-called stress-relaxation tests have been performed to demonstrate and investigate the local strains-total strains relationships with time, particularly, during the forward SIMT. Some remarkable phenomena have been observed pertaining to SIMT, which are absent in traditional materials and those unique phenomena have been explained qualitatively. For example, at the stopped loading conditions the two ends (fixed end and moving end of the tensile testing machine) were in fixed positions. So that there was no axial overall deformation of the specimen but some notable increase in the axial local deformation was shown by the extensometer placed at the middle of the SMA specimen. It should be noted that this peculiar behavior termed as 'inertia driven SIMT' occurs only when the loading was stopped at mixed phase condition. Besides this relaxation test for the SMA specimens, the same is performed for the mild steel (MS) specimens under similar test conditions. The MS specimens, however, show no unusual increase of local strains during the stress relaxation tests.

Keywords: SMA (Shape Memory Alloy); SIMT (Stress Induced Martensitic Transformation); stress relaxation; local strain; overall strain; inertia driven SIMT.

1. Introduction

Because of the unique property of superelasticity that depends on the stress induced martensitic transformation (SIMT), superelastic SMA can fully recover too large deformation upon withdrawal of the applied load. Consequently, termed as a unique functional material, it is extensively used for medical appliances, telephone antenna, head-band for head phones. That this excellent functional material can exhibit peculiar mechanical behavior under different loading conditions can be verified from the literature (Khan 2003, Rahman 2001, Rahman *et al.* 2001a, 2001b, 2002, 2005). For example, Rahman *et al.* (2001a, 2005) extensively demonstrated through experiment and numerical simulation that columns made of superelastic SMA have unique properties that are completely

---

† Associate Professor, Corresponding author, E-mail: ashiq@me.buet.ac.bd
‡ Assistant Professor

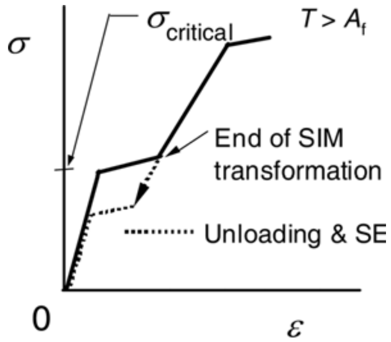

Fig. 1 Idealized stress-strain diagram of the superelastic SMA

absent in the columns made of other engineering materials.

Basic mechanical properties of the SMA and the phenomenon of stress-induced martensitic transformation are discussed below since those are closely related to the local deformation characteristics of the superelastic SMA rods.

Shape memory alloys are called active/functional materials because of their two unique capabilities, that is, the shape memory effect (SME) and superelasticity (SE). Both SME and SE mainly depend on the solid-solid, diffusion-less phase transformation process known as martensitic transformation (MT) from a crystallographically more ordered parent phase (austenite) to a crystallographically less ordered product phase (martensite).

The phase transformation (from austenite to martensite or vice versa) is typically marked by four transition temperatures, named as martensite finish (M_f), martensite start (M_s), austenite finish (A_f), and austenite start (A_s). For the SMA used in this study, $M_f < M_s < A_s < A_f$. For $T > A_f$, the SMA exists in the parent austenite phase. Under mechanical loading SIMT starts when a critical stress is exceeded. When SIMT is over the SMA exists in the martensite phase. This SIM phase is, however, unstable in the absence of stress at this temperature. Consequently, during unloading the initiation of reverse phase transformation is marked by another critical stress. When this reverse SIMT is complete the SMA returns to its parent austenite phase. The complete loading-unloading cycle shows a typical hysteresis loop (Fig. 1) known as pseudo-elasticity. It can be noted that the SIMT and the reverse SIMT are marked by a reduction of the material stiffness (Fig. 1).

For $T < A_s$, there is no pseudoelastic recovery but the residual strain can still be recovered by heating above A_f (SME). For any temperature there exists a critical stress for irreversible plastic slip to occur in the material (this critical stress value decreasing with increasing temperature), and if the stress is exceeded, the residual strain can't be recovered by heating or unloading. At room temperatures, usually, the superelastic Nitinol SMA can fully recover up to 6.5% strain.

As far as SIMT is concerned, experimental results reveal the fact that a unique relationship exists between the local and the overall deformations for the shape memory alloy (SMA) rods under tension pertaining to the forward and reverse SIMT (Khan 2003, Rahman *et al.* 2002, Tobushi *et al.* 2000). For instance, by tensile test of a wire, Tobushi *et al.* (2000) showed that during the forward SIMT and also during the reverse SIMT, the SMA behaves like an incompressible material. During loading there appears an interface between the austenite (parent phase) and the martensite (product phase) due to the SIMT. In SIMT, it is observed that the interface between a martensitic (*M*) phase and a parent austenitic (*A*) phase, which appears due to the action of stress, moves during deformation (Funakubo 1987, Leo *et al.* 1993, Shaw *et al.* 1995, Gadaj *et al.* 1999, 2002, Hutchinson 2000, Tobushi *et al.* 2000, Rahman *et al.* 2002).

In the experimental procedure of reference (Tobushi *et al.* 2000), the solid wire (diameter of 0.75 mm) was marked to identify ten different sections. During tensile test, a digital camera took photographs of the solid wire specimen. Necessary measurements were taken by a micrometer on the enlarged photographs to calculate the local longitudinal and lateral strains of the marked sections. Tobushi *et al.* (2000) showed the propagation of *A*-*M* interface continues up to almost 7% strain.

In the previous work Rahman *et al.* (2002) used highly sensitive strain gages to directly measure the local strains at a single position near the mid-portion of the solid wire. Use of strain gages in these cases has the added advantage of measuring the local strains directly and continuously with the change of load. Rahman *et al.* (2002) also showed that SIMT for the whole specimen is completed for an over all strain of 6.5%.

Sun *et al.* (2000) demonstrated two recent experimental discoveries on the local deformations of SMA. The first discovery is the spiral nucleation and propagation of martensite band in the micro-tube under uniaxial tension. The second one is the observation of the specimen size effect on the nucleation stress of macroscopic martensite band under superelastic deformation of wires.

Recently, Khan (2003) investigated local deformation of SMA during stress relaxation and creep tests. The present study, however, concentrates mainly on the interesting local deformations of the SMA during stress relaxation tests for forward SIMT. Stress relaxation test is particularly important for the superelastic SMA in the sense that it is repeatedly used in the appliances to undergo large deformations often for prolonged period.

Local deformation during SIMT is so remarkable that researches are still investigating to focus the same issue from different view points. For example, Tobusi *et al.* (2000) studied it by observing enlarged photographs of the specimen and then studied the same issue by measuring the temperature distribution (Pieczyska *et al.* 2004).

The above literature survey verifies the fact that the local deformation of SMA during SIMT is an excellent research topic for the active material community. This is because our understanding of what occurs locally in the pseudoelastic materials that experience large strains, is currently limited.

It is true that a number of studies are reported on the local deformation related to SIMT (Khan 2003, Rahman *et al.* 2002, Tobushi *et al.* 1999, 2000, Sun *et al.* 2000, Funakubo 1987, Leo *et al.* 1993, Shaw *et al.* 1995, Gadaj *et al.* 1999, 2002, Pieczyska *et al.* 2002, 2004). The following differences, between those studies and the present one, however, should be noted. As already discussed, the above-mentioned local deformation can be demonstrated by the sensitive strain gages (Rahman 2002), by measuring temperature (Pieczyska *et al.* 2004), or, by using micrometer on the enlarged photograph of the specimen under tension (Tobushi *et al.* 2000). Since during simple tension test deformation is associated with load, local deformation as well as total deformation are logical. But the stress relaxation test is completely different from simple tension test; in an ideal relaxation test no deformation, either local, or, total should be present. This paper, however, shows that local deformations are present during stress relaxation tests at different values of the local strains. It is noteworthy that the extensometer is not sensitive enough to show the above-mentioned local deformation during simple tension test (Khan 2003, Rahman *et al.* 2002), though the same extensometer can represent the unique local deformation during the stress-relaxation tests as highlighted in this study. No other researcher has reported this ‘local deformation during relaxation test’, so far as we know.

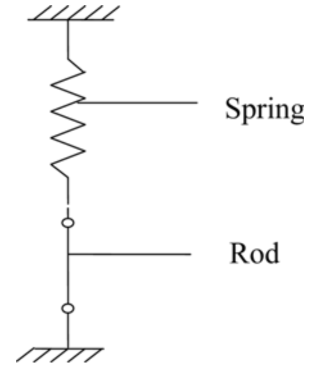

Fig. 2 Spring-rod arrangement for stress relaxation test

Another feature of this study is that, the relaxation tests were performed at different values of the local strains and the concerned results are presented. Whereas, no previous studies presented such test results (at different values of local strains). This is because of the fact that all of those previous studies involved simple tension test, very much different from a stress relaxation test.

Moreover, this unique local deformation during forward deformation may lead to inertia driven SIMT as pointed out in the later sections of this study.

By definition, stress relaxation is a phenomenon of decreasing stress with constant strain over a given time interval (viscoelastic response). The general stress relaxation test is performed by isothermally loading a specimen to a fixed value of constraint. The constraint is maintained constant and the constraining force is determined as a function of time.

This can be illustrated using simple models. A rod of unit length and unit cross-sectional area is connected in series with a spring of stiffness c as shown in Fig. 2. Initially the rod is subjected to an elongation e_o and the stress in it is σ_o. The elongation of the spring is then σ_o/c. Thereafter the sum of the elongations of the specimen and of the spring remains constant, consequently,

$$e + (\sigma/c) = e_o + (\sigma_o/c) = \text{constant} \tag{1}$$

If the material of the rod creeps, its elongation is accompanied by a reduction in stress because the energy of the system cannot increase. This process of stress diminution with time is termed stress relaxation. If the spring is not very stiff the displacement of its end that is associated with elongation of the specimen has little influence on the tensile force of the spring. Therefore, the stress in the specimen remains constant and the conditions are similar to those of a typical creep test. In the other extreme case, the spring is extremely stiff and the second terms in the left and right-hand side of the Eq. (1) become negligible. The total length of the specimen remains constant and it follows from the equation that, e = constant. This case is pure relaxation (Rabotnov 1969).

According to the ASTM (1991) stress relaxation is the time-dependent decrease in stress in a solid under given constraint conditions. ASTM test methods cover the determination of the time dependence of stress (stress relaxation) in materials under conditions of approximately constant constraint, constant environment and negligible vibration. The general stress relaxation test is performed by isothermally loading a specimen to a fixed value of constraint. The constraint is maintained constant and the constraining force is determined as a function of time. The major problem in the stress relaxation test is that constant constraint is virtually impossible to maintain and considerable attention must be given to minimize the constraint variation.

2. Experiment

Before performing the stress relaxation test, the typical unique local deformation was demonstrated through tension test of an SMA specimen using an Instron machine for loading and strain gages for measuring the local strains. The strain rate during loading-unloading was 0.015/min. Gage length for the specimen was 130 mm. The strain gage placed at the middle of the specimen can measure up to 15% strain. It should be mentioned here that extreme care and skill are necessary to perfectly glue the strain gages to such small diameter specimens. The strains were measured simultaneously by the strain gages and displacement of the fixtures.

A mechanical extensometer was also used to measure the local strain at the middle of other SMA specimens, particularly for relaxation test. The length of each of these specimens was 445 mm. The sensitivity of the extensometer was 0.005 mm and its gage length was 50 mm. It can measure up to 5% strain. Tinius Olsen machine, was used to conduct the relaxation tests. This machine is actuated by an electric motor. The forward actuation (loading) and the reverse actuation (unloading) can be started and stopped at any position through electric switching mechanism. Therefore clamped-clamped end constraint can be maintained with a loaded specimen in between the grippers. A dial gauge with gauge constant of 0.01 mm was used to measure the overall strain. The deformation range of the gauge is 0-25 mm (Fig. 3).

Thus, the relationships between the local and overall deformations have been traced continuously particularly for the forward SIMT during the stress relaxation tests. The terms ‘stress-relaxation test’ or, ‘loading stopped at a certain value of local strain’ have been used to indicate that the tensed specimen was held between two immovable grippers for certain time period.

The specimens used in the experiment were superelastic SMA rods (Ti 49.3 at%, Ni 50.2 at%, V

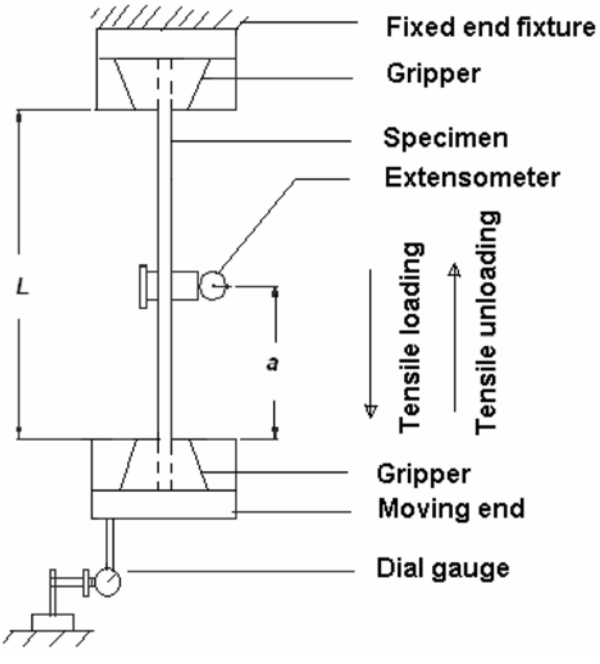

Fig. 3 Schematic diagram of relaxation test setup in tension

0.5 at%), and Mild steel (MS) strips. The length and diameter of the SMA (NiTi) specimen were 445 mm and 2 mm, respectively. SMA's transformation temperatures are −59°C, −34°C, −27°C and −3°C for the martensite finish, martensite start, austenite start and austenite finish, respectively. Average measured Young's Modulus for the parent phase was 65 GPa.

The length of the MS specimen was 305 mm with a cross-section of 1.4 mm × 5.35 mm. Average measured Young's Modulus was 180 GPa. All the tests were performed at room temperature of 23°C −30°C, ensuring superelasticity of the SMA.

The strain rate during relaxation test was 7.5×10^{-5}/ sec. For the SMA rods loading-unloading cycles were completed with loading stopped at 1%, 3%, 3.5%, 3.75%, 4% local strains, in order to perform the stress relaxation test of the rods. The behavior of SMA during that test period has been investigated, presented and compared with that of a traditional material (MS) through the similar experimental procedure.

3. Results and discussions

Before discussing the stress relaxation test results, it is interesting and important to demonstrate the typical unique local deformation characteristics of the SMA for simple tension tests. As can be seen from Fig. 4, the relationship between the local and overall strains is almost linear up to a strain of 4.75%, if the local strain is measured by the extensometer. This all-through linear relationship is the usual trend for all known engineering materials.

In contrast, if the local strains are measured by much more sensitive strain gages, the unique local strains-overall strains relationship can be observed distinctly from Fig. 4. As seen, initially the relationship between the two readings is linear. However, after approximately 1% strain is exceeded, quite remarkably, there is almost no local strain although there is end displacement. Actually, it indicates that the local SIMT is initiated. When the SIMT is about to finish, the part, which did not expand earlier suddenly increases rapidly. Thus the two points may verify the starting and finishing end points of the transformation process. Tobushi *et al.* (2000) showed that during the SIMT, the Poisson's ratio approaches 0.5, implying the condition of no-volume change or, incompressibility has been reached locally. The horizontal portion of Fig. 4 also verifies the above mentioned fact.

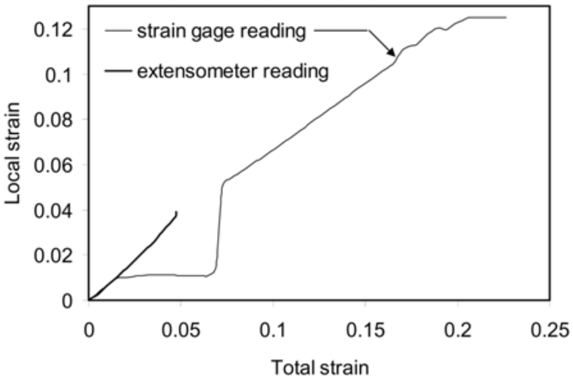

Fig. 4 Simple tension test results for local strain vs. total strain for the SMA rods

The above observations verify the fact that the size and accuracy of the local strain measuring instrument are extremely important as far as this unique local deformation of the superelastic SMA is concerned. Therefore, it can be concluded that the tiny strain gages with high sensitivity, glued to the surface of the rod can more effectively measure the local deformations in comparison with an extensometer.

In the subsequent paragraphs the main contribution of this study, that is, the results of stress relaxation tests are discussed. It should be mentioned here that all the stresses referred to here are nominal stresses and the local and overall strains are axial nominal strains. No change in the dial gage reading placed at the gripper end indicates clamped-clamped ends (overall axial strain is constant). Before the relaxation tests, the SMA specimens had undergone a few (6 to 10) loading-unloading cycles. As already shown in Fig. 4, for the same specimen, SIMT starts from 1% strain. It should be noted that critical stress decreases with increased number of loading unloading cycles for the same specimen. Typically, the plateau stress decreases markedly in the early cycles but approaches a certain saturated value afterwards (Tobushi *et al.* 2000, Gong *et al.* 2000).

Fig. 5 shows the nominal stress-strain curve of SMA specimen for stress relaxation tests followed by complete unloading. The local strain was measured at the mid position of the specimen. Here the stress-strain relation is almost proportional up to approximately 1% of the strain but after that the strain increases with a very little increase in the stress. The loading was stopped at 4% strain (the corresponding overall strain was 4.55%). At this stopped loading condition the two ends were in fixed positions, resembling typical relaxation test. Though there was no axial overall deformation of the specimen but some notable increase in the axial local deformation was shown by the extensometer. This remarkable increase of strain with a slight fall of stress can be observed also for other cases if the relaxation test is performed beyond 1% local strain, that is, in the mixed phase region, as shown in Fig. 5. Therefore, one important point can be concluded from the present study: since local strains do change during stress relaxation test, it prevents one from assuming that the unique local deformation characteristics during simple tension test (which has also been demonstrated in this present study also) are due to necking. After the completion of the relaxation test, when unloading starts, the reverse transformation starts at a lower stress level and continues up to 1% strain. After the completion of unloading material returns to its original state which indicates the superelastic property of SMA.

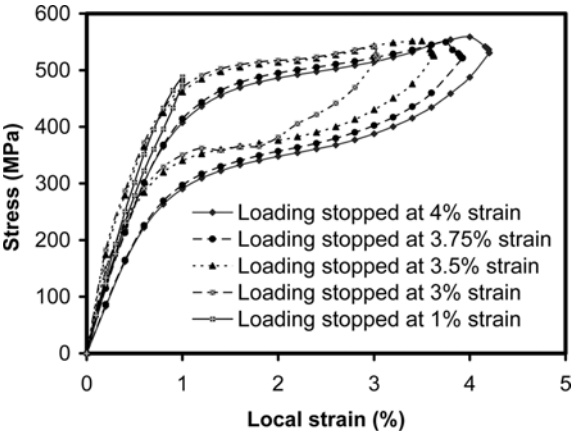

Fig. 5 Stress-local strain hysteresis for the SMA rods showing also the stress-relaxation tests

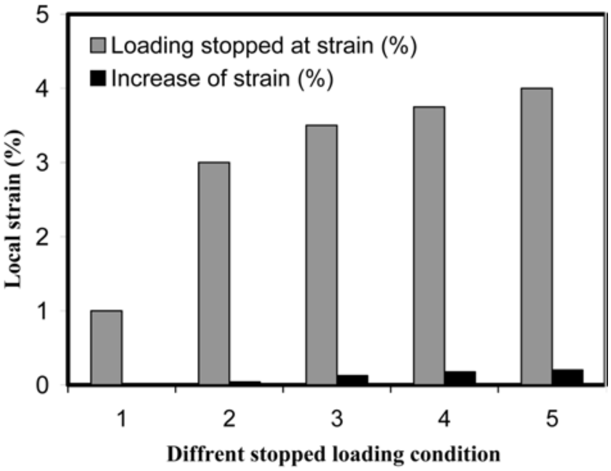

Fig. 6 Increase of % of local strain at mid position for relaxation tests performed at various local strains for the SMA rods

Though all the results are not presented here, briefly, the behavior of SMA was found similar when the loading was stopped at 4%, 3.75%, 3.5%, and 3% of local strains. In each of the stopped loading conditions, there was an increase of local strain with decrease in stress level. But the magnitude of increase of local strain with respect to time is different as evident from Fig. 6. For the relaxation test at 4% local strain the magnitude of increase in the local strain was found to be the maximum. It was 0.2% and the value decreases gradually to 0.17%, 0.12%, and 0.04% for the relaxation tests performed at 3.75%, 3.5%, 3% local strains, respectively. The rate of increase of local strain was 0.08%, 0.065%, 0.033%, and 0.00875% per minute for the relaxation tests performed at 4%, 3.75%, 3.5% and 3% local strains, respectively.

Another test result as presented in Fig. 7 shows that when the loading was stopped at 1% local strain for SMA, there was no increase of local strain with fall of stress, indicating that that portion of the material is still in the parent austenite phase. At this condition (before the start of SIMT) the material's behavior is very much similar to a traditional material except the superelasticity.

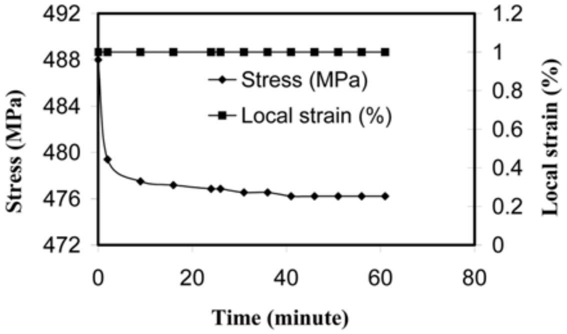

Fig. 7 Stress and local strain at mid position versus stopped loading time curve for the SMA rods (relaxation test performed at 1% local strain)

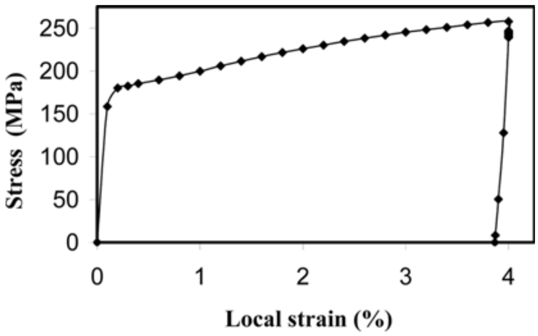

Fig. 8 Stress - local strain curve for the MS specimen showing stress-relaxation test

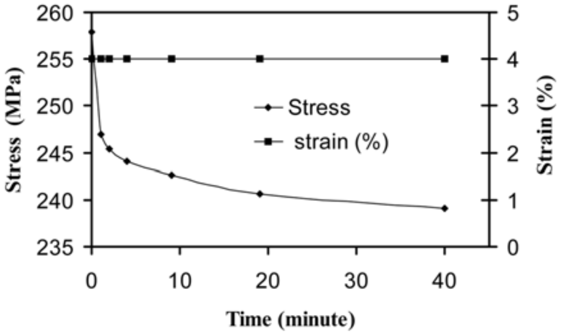

Fig. 9 Stress and strain at mid position versus time curve for the MS specimen (relaxation test performed at 4% local strain)

Stress-relaxation test results for the MS specimen are shown in Figs. 8 and 9. For this test, loading was stopped at 4% local strain. As seen, the unloading curve after the relaxation test is almost parallel to the initial loading curve. There was no increase of local strain with fall of stress and this phenomenon is similar when the loading for SMA was stopped at 1% local strain. Table 1 shows a comparative picture for the SMA and MS specimens under similar test conditions. It is also important to note that this decrease in stress (termed as, relaxation loss) is much more for the MS specimens.

Fig. 10 shows the changes of the stress and local strain with respect to time for the SMA and MS specimens. Here the local strain increases from 4% to almost 4.2% and the stress decreases from 558 MPa to 530 MPa within one hour after the loading was stopped. Though less prominent, almost similarly this unique phenomenon occurs when the loading was stopped at 3.5% local strain. Therefore, strain rise is more if relaxation test starts when the SIMT is near to finish. The pattern of the curve indicates that initially in the first 2 minutes the increase in the strain and decrease in the stress are very rapid but slow down gradually. As expected, MS specimens on the other hand, show relaxation loss with constant local strain (Figs. 8-10 and Table 1).

Stopping the loading at 4% local strain means that the material in that portion is still in the mixed phase condition. But as the local strain increases rapidly with a very small change in the load, it appears that the SIMT that started after almost 1% of strain, does not stop even when the loading was stopped. The transformation continues to some extent even though there was some fall of load.

Therefore, for SMA and other traditional materials like MS, distinct features have been found

Table 1 Comparison of stress relaxation loss (%) of SMA and MS specimens for one hour (The values are the average of five experimental results)

Material	Test conditions	Stress relaxation loss (%)
SMA	Loading stopped at 3.50% local strain	4.90
MS	Loading stopped at 3.50% local strain	7.78
SMA	Loading stopped at 4.00% local strain	5.07
MS	Loading stopped at 4.00% local strain	7.50

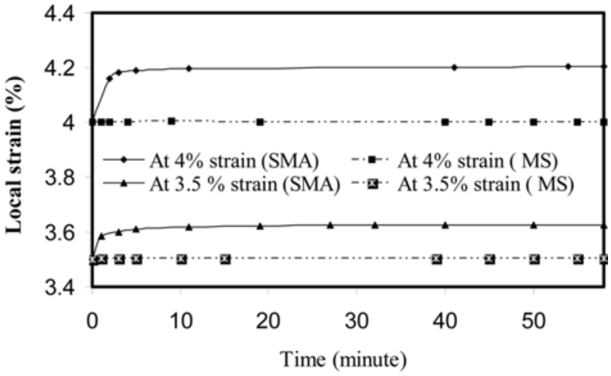

Fig. 10 Local strain verus time curves for the SMA and MS specimens for stress-relaxation tests performed at 4% and 3.5% local strains

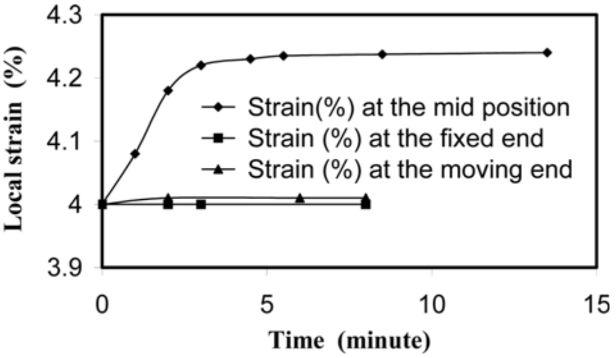

Fig. 11 Local strain versus time curve for the SMA specimens at diffrent positions (relaxation tests performed at 4% local strain)

through similar experiment of stress relaxation. MS shows fall of stress with no change in local strain whereas SMA shows fall of stress with remarkable increase in local strain when it is in mixed phase condition. But there is no significant increase in local strain if it is in parent austenite phase. This present experimental observations together with the previous studies provide the brief scenario to the deformation process. It can be said that the movement of the interface continues when the loading is stopped at mixed phase region, with subsequent fall of stress. This phenomenon may be termed as inertia driven transformation of prematured martensite (or, inertia driven SIMT).

When the volume fraction of martensite is very small there is a very weak interaction among the transformed martensite products. With the increase in stress and martensite volume fraction this elastic interaction increases with subsequent increase in the transformation inertia effect, evident by the present experimental results.

Fig. 11 shows the comparative curves of local deformations of SMA for the mid position, near the fixed end and also near the moving end after the loading was stopped at 4% local strain. It is clear from the figure that there is significant change in local strain at mid position but no significant change occurs near the two ends. When the material at mid portion is in the mixed-phase condition, the portion of the same material near the ends might finish the SIMT. Presumably this is because of stress concentration near the two ends.

4. Conclusions

As far as stress relaxation is concerned, through this present experimental investigation a unique phenomenon has been demonstrated which is named as inertia driven SIMT. It is found that during the stress relaxation tests (i) local strain increases with decrease of load at the mixed-phase condition, (ii) increase of local strain and strain rate depend on the volume fraction of martensite (iii) strain rate is very high at initial time period but slows down gradually (iv) at single phase condition (Austenite) the behavior of the local strain is similar to that of a traditional material. In this experiment extensometer was used to observe the change in local strain. Therefore, it will be interesting to observe these phenomena by using more precise strain gages. This is because, as far as deformation of SMA during simple tension test is concerned, this study has also proved that the sensitive strain gages can effectively demonstrate the unique local strain-overall strain relationships.

Stress relaxation test results for the MS specimens under similar test conditions show relaxation loss is more for the MS than it is for the SMA. The MS specimens, however, do not show the remarkable increase of local strains during the tests.

Finally, one important point can be concluded from the present study: since local strains do change during stress relaxation test, it prevents one from assuming that the unique local deformation characteristics during simple tension test (which has been demonstrated even in this present study also), is due to necking.

Acknowledgements

Test concerning only the strain gages was conducted at the Institute of Fluid Science, Tohoku University, Sendai, Japan. Major contribution of this study concerning the stress relaxation tests was performed at the Strength of Materials Laboratory, Department of Mechanical Engineering, BUET. The authors are grateful to Professor Junji Tani, Institute of Fluid Science, Thohoku University, for providing the SMA specimens.

References

FunaKubo, H. ed. and Shape Memory Alloys (1987), Gordon and Breach Science, New York, 39-41.

Gadaj, S.P., Nowacki, W.K. and Tobushi, H. (1999), "Temperature evolution during tensile test of TiNi shape memory alloy", *Arch. Mech*., **51**(6), 649-663.

Gadaj, S.P., Nowacki, W.K. and Pieczyska, E.A. (2002), "Temperature evolution in deformed shape memory allow", *Infrared Physics & Tech.*, **43**, 151-155.

Gong, J., Tobushi, H., Takata, K. and Okumura, K. (2000), "Superelastic properties of TiNi shape memory alloy under various loading conditions", *Proc. of the 11th ICAST* (Nagoya).

Hutchinson, J.W. (2000), "Plasticity at the micron scale", *Int. J. Solids Struct.*, **37**, 255-238.

Khan, R.M. (2003), "Investigation of local strain of the superelastic shape memory alloy rods for tensile loading-unloading cycles", M. Sc Engg. Thesis, Bangladesh University of Engineering & Technology, Dhaka.

Leo, P.H., Shield, T.W. and Bruno, O.P. (1993), "Transient heat transfer effects on the pseudoelastic behavior of shape memory wires", *Acta Metall. Mater*., **41**(8), 2477-2485.

Pieczyska, E.A., Gadaj, S.P. and Nowacki, W.K. (2002), "Thermoelastic and thermoplastic effects in steel, polyamide and shape memory alloys", *Proc. of SPIE's AeroSense*, **4710**, 479-487.

Pieczyska, E.A., Gadaj, S.P., Nowacki, W.K. and Tobushi, H. (2004), "Transformation in TiNi shape memory alloy", *Bul. of the Polish Academy of Sciences*, Technical Sciences (3), 165-171.

Rahman, M.A., Tani, J. and Qiu, J. (2002), "Direct method to estimate stress induced-martensitic transformation points by tensile test", *Proc. of BSME-ASME- Int. Conf. on Thermal Engineering*, Dhaka, Bangladesh. 761-765.

Rahman, M.A., Qiu, J. and Tani, J. (2001), "Buckling and postbuckling characteristics of the superelastic SMA columns", *Int. J. Solids Struct.,* **38**, 9253-9265.

Rahman, M.A. (2001), "Behavior of the superelastic shape memory alloy columns under compression and torsion", Ph.D. Thesis, Tohoku University, Japan.

Rahman, M.A., Qiu, J. and Tani, J. (2005), "Buckling and postbuckling characteristics of the superelastic SMA columns-numerical simulation", *J. Intelligent Material Systems and Structures*, **16**(9), 691-702.

Rahman, M.A., Tani, J. and Qiu, J. (2001), "Unique behaviors of the superelastic shape memory alloy under tensile and compressive loading", *Proc. of Int. Conf. on Mechanical Engineering*, Dhaka, Bangladesh. **3**(5), 185-187.

Rabotnov, Y.N. (1969), *Creep Problems in Structural Members*, North Holland Publishing Company. Amsterdam, London.

Shaw, J.A. and Kyriakides, S. (1995), "Thermomechanical Aspects of NiTi", *J. Mech. Phys. Solids*, **43**(8), 1243-1281.

Standard Methods for Stress Relaxation Tests for Materials and Structures, ASTM Designation: E 328-86 (Reapproved 1991)

Sun, Q.P., Li, Z.Q. and Tse, K.K. (2000), "On superelastic deformation of NiTi shape memory Alloy Micro-tube and wires band nucleation and propagation", *Proc. of IUTAM Symposium on Smart Structures and Structronics Systems*, Magdeburg, Germany, Sept., 26-29.

Tobusi, H., Okumura, K., Endo, M. and Takata, K. (2000), "Stress-induced martensitic transformation behavior and lateral strain of TiNi shape memory alloy", *Proc. of the 11th ICAST* (Nagoya), 367-374.

Tobushi, H., Takata, K., Shimeno, Y., Nowacki, W.K. and Gadaj, S.P. (1999), "Influence of strain rate on superelastic behavior of TiNi shape memory alloy", *Proc. Instn. Mech. Engrs*., **213**(L), 93-102.