CYCLIC PLASTIC DEFORMATION BEHAVIOUR OF PHT PIPING MATERIALS – AN EXPERIMENTAL INVESTIGATION

S. Sivaprasad[a], Surajit K Paul[b], S. Tarafder[a], Suneel K Gupta[c], Vivek Bhasin[c]
[a] MST Division, CSIR-National Metallurgical Laboratory, Jamshedpur 831007
[b] R & D Division, Tata Steel, Jamshedpur 831001
[c] RSD Division, Bhabha Atomic Research Centre, Mumbai
email of corresponding author: shiva@nmlindia.org (S. Sivaprasad)

ABSTRACT

The work presents the cyclic plastic deformation behaviour of two varieties of primary heat transport piping materials to understand the hardening/softening behaviour, load history memory, strain range effect, mean stress effect and ratcheting behaviour. Microstructural changes during cyclic deformation manifest in cyclic expansion of yield that could be used to explain the hardening/softening behaviour. Both the materials memories the prior history, however, the effect disappears after some time. Both the steels exhibit non-Masing behaviour due to inhomogeneous substructural changes. Non-Masing behaviour could be explained through cyclic expansion of yield. Engineering stress controlled ratcheting experiments were noted to be inadequate and under predict the ratcheting fatigue life. Importance of true stress controlled ratcheting experiments were discussed.

INTRODUCTION

Engineering components are often subjected to cyclic load excursions and the cyclic plastic deformation of engineering materials thus becomes inevitable. Since the resultant elastic-plastic stress-strain response of the material plays a pivotal role in analysis of design and failure of the component, it becomes important to understand the cyclic plastic deformation behaviour of engineering materials. There are numerous evidences that the process of damage accumulation due to cyclic loading is greatly influenced by the evolution of dislocation sub-structure (for e.g., 1-3) and the degree of damage is influenced by a number of factors such as type of loading, presence of stress riser and residual stress. In spite of great deal of efforts, especially in the last two decades, to understand the various aspects of cyclic plasticity and their constitutive modeling, there are still difficulties in translating the knowledge gained to different material systems. One of the primary reasons for this inability is due to the complex nature of the cyclic plastic phenomena and its strong dependency on material characteristics, and it thus becomes essential to deal with all common factors that control the plastic deformation in different materials. This paper is aimed at addressing some of these key issues that control the cyclic plasticity. While all these aspects are widely accepted by the research community in the subject area, they have been revisited in light of our recent experimental investigations.

In general, the cyclic plasticity is governed by various material behaviour such as cyclic hardening/softening, load history memory, strain range effect (Masing/non-Masing behaviour), mean stress relaxation, ratcheting etc. In this work experimental investigation has been carried out on two varieties of primary heat transport piping materials to understand these phenomena. Special emphasis has been given to cyclic ratcheting, considering its importance in fatigue life design. The significance of true stress controlled ratchetting experiments over that of engineering stress controlled ratcheting studies have been examined.

The overall objective of this work is to provide a fundamental understanding of the cyclic plastic phenomena, considering various material aspects that are experimentally observed. Such understanding is expected to present a basic guideline for development of constitutive relationships for cyclic plasticity.

EXPERIMENTAL

The materials used in this investigation are (i) 304LN austenitic stainless steel and (ii) SA333 Gr.6 C-Mn steel. Both the materials were available in the form of pipes with 340mm outer diameter x 25mm wall thickness (304LN stainless steel) and 600mm outer diameter x 50mm wall thickness (C-Mn steel). The chemical composition (wt.%) of the 304LN stainless steel was C 0.03; Si 0.65; Ni 8.17; Mo 0.26; Cu 0.29; N 0.08; S 0.02; P 0.034 while that of the C-Mn steel was C 0.18; Mn 0.9; Si 0.02; P 0.02.

Solid specimens of 7mm gauge diameter and 13mm gauge length were fabricated from the pipe sections such that the loading axis of the specimen is parallel to the length of the pipe. All strain controlled experiments were conducted using a triangular waveform at a constant strain rate of 10^{-3} s^{-1}. All stress controlled experiments were conducted at a constant stress rate of 50MPa/s employing a similar waveform. A 100kN closed loop servo-electric test system was used for all the studies employing a 12.5mm gauge length extensometer. All experiments were conducted in room temperature and approximately about 200 data points per cycle were collected for further analyses.

RESULTS AND DISCUSSIONS

Cyclic hardening/softening behaviour

Alteration in the stress response of a material subjected to strain cycling is referred as cyclic hardening/softening behaviour. One of the major factors that control the ability of a material to cyclically harden/soften is its microstructural constituents and their participation in the deformation process. The phenomena is very complex in polycrystalline materials due to the own mechanical properties, ordering direction and directional properties of each grain. One of the most convenient methods to understand the hardening/softening behaviour is to examine the manner in which the stress amplitude varies with the loading cycles. This is shown in Fig 1(a) and (b) for SA333 C-Mn steel and 304LN stainless steel respectively for various strain amplitudes. 304LN steel shows a different combination of initial hardening followed by softening, whereas SA333 C-Mn steel shows cyclic hardening throughout its life. It may be noted that the two materials have different crystal structures (SA333-*bcc*; 304LN-*fcc*) and possess different phase constituents (SA333-ferrite-pearlite; 304LN-austenite). Obviously, the dislocation generation and their subsequent movement upon deformation are liable to be different in the two materials and therefore a different deformation characteristic.

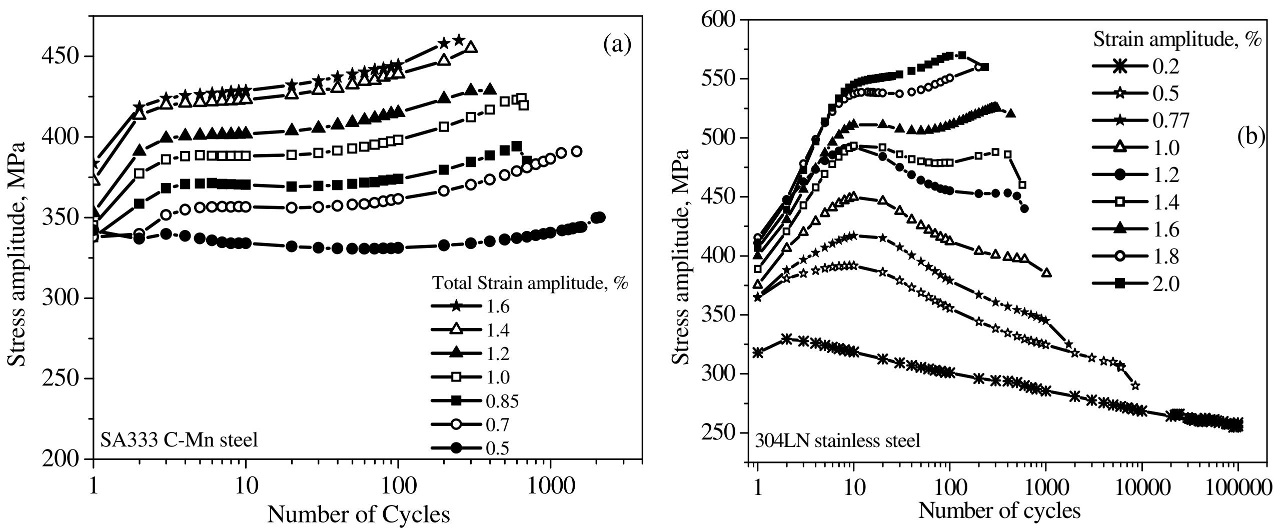


Figure 1: Cyclic hardening: strain amplitude versus number of cycles plot
(a) SA333 C-Mn steel (b) 304LN stainless steel

The initial hardening in the C-Mn steel can be attributed to the rapid multiplication of dislocation upon cyclic deformation while that in 304LN stainless steel apart from dislocation generation to the partial transformation of austenite to martensite that impede smooth dislocation movement. The subsequent softening can be related to the re-arrangement of the dislocation network. With progressive deformation, refinement of dislocation arrangement can lead to finer dislocation cell formation. In effect, the original grain is divided into a number of sub-grains, thereby confining the dislocation movement. The stress therefore increases, causing the material to harden. This indicates that the cyclic deformation and the hardening/softening behaviour are dependent upon the microstructural constituents described above and their interaction during the deformation event. Figures 2 (a) and (b) shows the sub-cell formation within the ferrite grain (SA333) while that in 304LN formation of both ε and α martensite in the failed sample of LCF test after confirmation from selected area diffraction pattern analyses. This microscopic study supports the above mentioned explanation of cyclic hardening behaviour.

The overall material hardening/softening behaviour resulting from the local alterations in substructure is generally modeled through yield stress variation [2,4]. To verify this, the stress-strain hysteresis loops of different cycles are translated in such a manner that a common linear regions of the loading branches of all the cycles coincide and a universal envelope curve can be drawn to describe the loading branches. It is noted that a systematic cyclic expansion of the yield occurred and the hardening/softening can be explained by this change in cyclic yield.

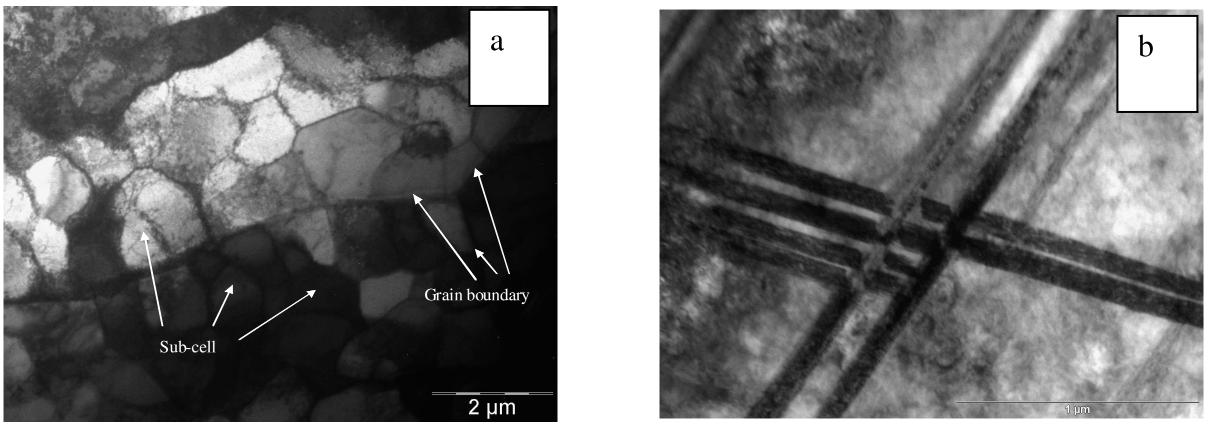


Figure 2: TEM pictures of (a)SA333 showing sub cell formation (b)304LN showing formation of martensite at intersecting slip bands

Load history memory

To verify the influence of prior load history on the cyclic stress-strain response, fully reversed strain controlled cyclic deformation studies were performed on (i) specimens tensile pre-strained to different pre-determined strains and (ii) on specimens cyclically pre-strained at a constant pre-determined strain (i.e. high to low step loading). The cyclic pre-strain was carried out under strain control analogous to the low cycle fatigue procedure except that the cyclic deformation was imposed for a pre-determined number of cycles. The influence of tensile pre-strain on cyclic deformation behaviour of SA333 Gr.6 steel is shown in Fig. 3(a) along with base line fatigue data (without any prior history effect) and that of the cyclic pre-strain in Fig 3(b) for the same material.

The results infer that after the imposition of tensile pre-strain, the stress response during subsequent cyclic deformation under strain control is completely altered. The base line data showed significant hardening upon cyclic deformation, whereas after imposition of pre-strain, the material exhibits softening behaviour. As the magnitude of the pre-strain is increased, the cyclic stress response was also noted to be high. This increase is significant for the first few cycles when compared to the base line cyclic response. This implies that the material memorizes the prior loading history and influences the subsequent hardening/softening response. The material memory, however, gradually fades away with subsequent cycles and finally converges with the base line stress response (i.e., stabilized hysteresis loop).

Similar to the tensile pre-straining, cyclic hardening/softening behaviour also gets altered with high to low (i.e. high strain amplitude to low strain amplitude) step loading as shown in Fig. 3(b). Single step LCF with 0.7 % strain amplitude shows cyclic hardening throughout its fatigue life, whereas 0.7 % strain controlled LCF with 20 cycles of pre-LCF reversal (1.6% amplitude) shows cyclic softening in initial few cycles and after that slow cyclic hardening throughout its life as observed in pure LCF condition.

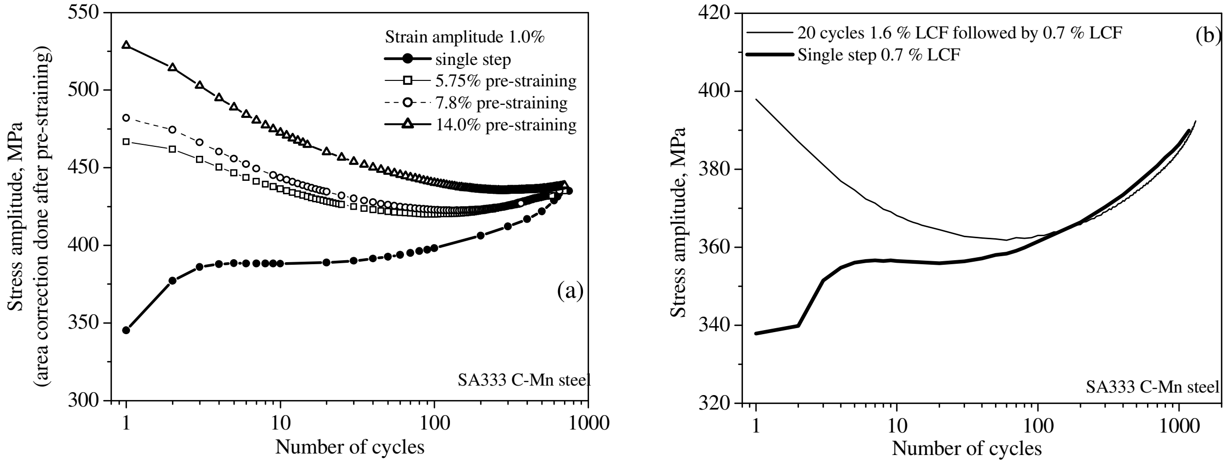


Figure.3: Influence of (a) tensile pre-strain and (b) cyclic prestrain on fatigue life.

Strain range effect

Experimentally, Masing behaviour in a material is verified by bringing the compressive tips of (sometimes the tensile tips) all the stable hysteresis loops belonging to various strain amplitudes to a common origin. If all the loading branches (or unloading branches in case of translating tensile tips) overlap and form a common envelope curve – termed as Master curve, then the material is said to follow Masing model [5]. The results for the two steels in this investigation are shown in Fig 4.(a) and (b). It can be seen from these figures that both 304LN stainless steel and SA333 Gr.6 steel exhibit non-Masing behaviour. Masing behaviour is not a universal phenomenon in engineering materials. Plumtree et al. [6] have shown that some materials exhibit Masing behaviour while others do not. Fan and Jiang [7] noted Masing behaviour in a pressure vessel steel at 300^{o}C and 420^{o}C. Maier et al. [8] observed Masing behaviour in an ultrafine grained copper.

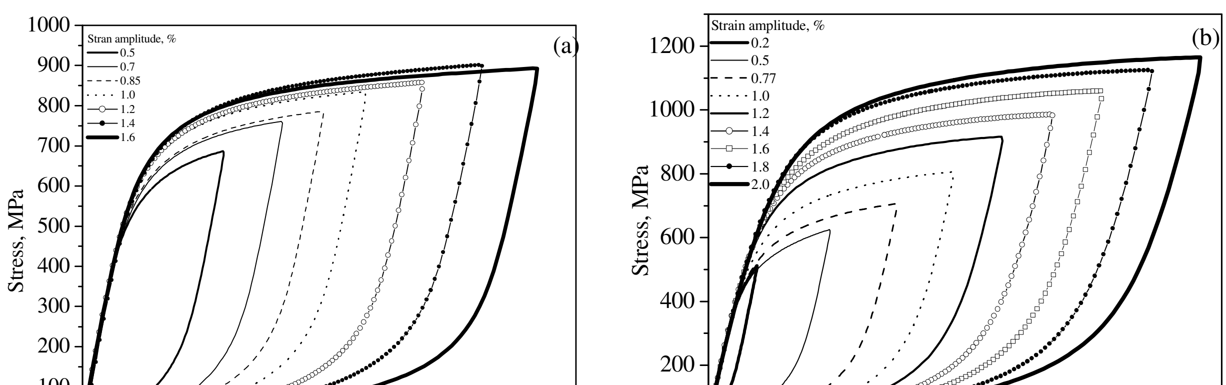
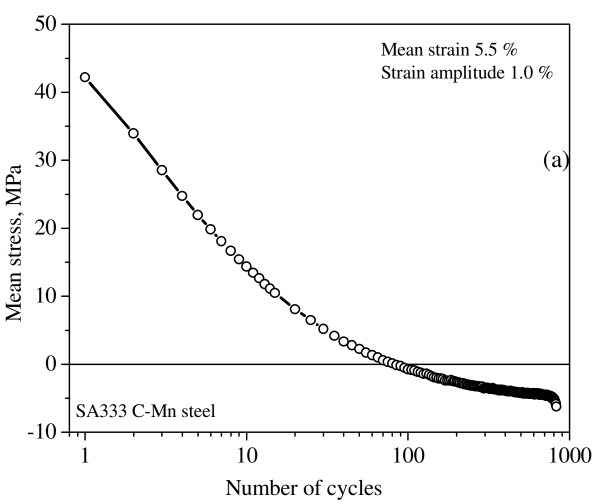


Figure 4: Non-Masing behaviour in (a) SA333 steel and (b) 304LN stainless steel.

From microscopic point of view Masing behaviour relates to a stable microstructural condition and dislocation substructure [9] against fatigue cycles. In a study of hysteresis loop shapes for different metals and alloys [6], it was noted that non-Masing behaviour was observed for group of metals and alloys in which cyclic deformation is controlled by matrix properties, and dislocation cells are formed at relatively low strain ranges. In addition, Mughrabi and Christ [10] have pointed out that phase stability is a pre-requisite for the Masing phenomena. Investigations on microstructural changes during cyclic deformation and observations of dislocation cell development [11] showed that both the microstructural phase constituent and the dislocation cell size need not necessarily remain stable upon cyclic deformation in all materials. The stainless steel investigated in this work belongs to this category. Such instability will produce a deviation from Masing behaviour. In materials that do not suffer phase transformation upon cyclic deformation (such as the C-Mn steel in this work), the non-Masing behaviour is considered mainly due to heterogeneous dislocation arrangement. Observations of dislocation arrangements during cyclic deformation at different strain amplitudes in many materials [1,9,11] showed a gradual change in dislocation cell structure with the dislocation density (dislocation veins) within the cell interior gradually depleting. The material within the cell interior is therefore expected to be soft. The cell walls representing regions of high dislocation density is expected to possess high yield level. Such a material can be treated as a composite consisting of hard and soft regions strained in parallel as proposed by Masing model [9]. Such transient dislocation cell structure and/or phase instability can introduce additional yield levels upon cyclic deformation thereby introducing a deviation from Masing behaviour. In general, Masing phenomena requires a stable microstructual event. A microstructural event here refers to both phase stability and stable dislocation density. Any deviation from this basic requirement is an indication that conformity to Masing behaviour will not be maintained. Our analyses have shown that the deviation from Masing in both the steels can be explained by the cyclic expansion of the yield and can be modeled using energy based concepts. Moreover, it has also been observed that multiple yield levels are being introduced in both the materials upon cyclic deformation that is responsible for the non-Masing behaviour. An explanation for the non-Masing behaviour in both the materials could be provided through probability distribution of yield levels.

Mean stress relaxation

During asymmetric strain cycling, the presence of a constant mean strain, would introduce a mean stress that would relax gradually upon progressive cyclic deformation [12]. Mean stress relaxation during asymmetric strain cycling with a mean strain of 5.5% and strain amplitude of 1% has been examined. The results showed that the presence of tensile mean strain influences the tensile peak stress that relaxes with progressive cycles. The compressive peak stress remains unaltered. It will be interesting to also know if mere presence of mean strain influences the peak stress irrespective of the manner in which it is imposed or not. To verify this, we additionally performed an experiment in which a specimen was tensile pre-strained to 5.75% total strain and was followed by imposition of 1% symmetric strain cycling. The magnitude of the tensile pre-strain (5.75%) selected was such that it resulted in a residual strain of ~5.5% upon loading which is equivalent to the mean strain level reported in Fig. 5. A comparison of the two results is given in Fig. 5b. The results show that the material response is similar in both the cases indicating the fact that mean stress relaxation depends mainly on the magnitude of mean strain irrespective of the manner in which it was induced



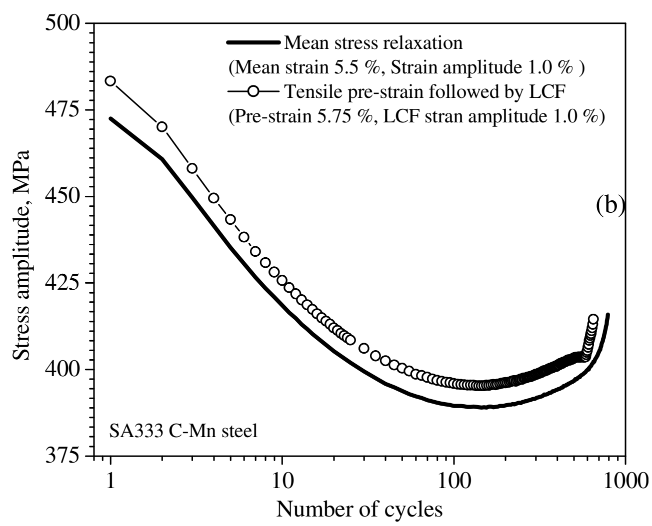


Figure 5: Mean stress relaxation at mean strain of 5.5% and strain amplitude of 1.0% on SA333 C-Mn steel (a) mean stress variation with number of cycles (b) Change in stress amplitude with cycling and comparison with monotonic pre-straining 5.75% followed by 1.0% symmetric strain cycling.

Uniaxial ratcheting

A number of investigations have been carried out in the last two decades [13-18] to understand and model the material ratcheting behaviour. In a majority of investigations, including the works cited above, the ratcheting behaviour has been investigated employing a cyclic waveform under load or engineering stress control that is based on the original dimensions of the specimen. For high magnitudes of mean stress and stress amplitude, the accumulated strain over a period of time may be reasonable to produce a considerable change in the specimen cross-sectional area. If appropriate correction factors are not accounted for these dimensional alterations, the true mean stress and true stress amplitude are liable to increase uncontrollably, leading to overload failure of the specimen rather than due to ratcheting fatigue. The life prediction will therefore be inappropriate. To examine this factor, a series of uniaxial experiments were carried out under both engineering and true stress control to bring out the difference in life. A comparison of one set of such experiment in 304LN and SA333 Gr.6 steels is shown in Fig. 6.

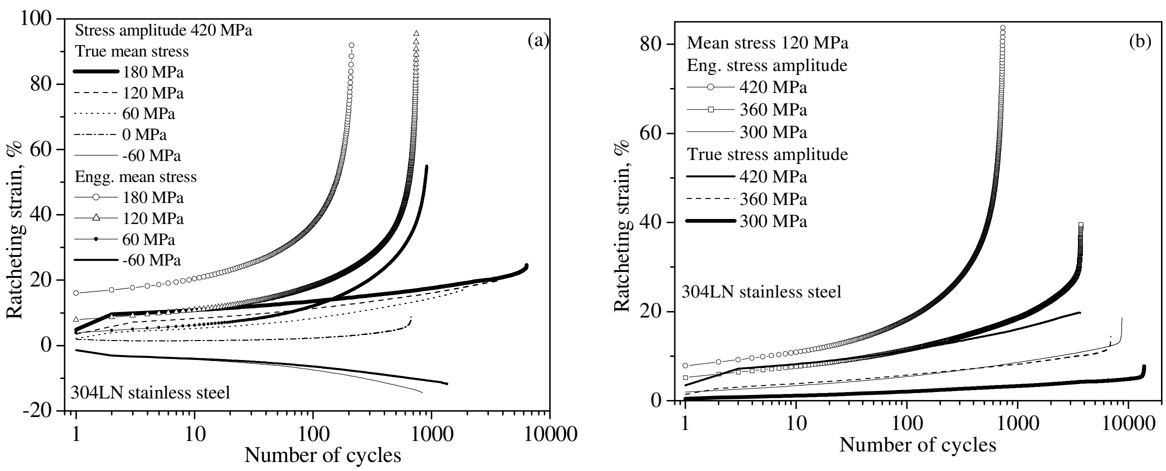


Figure 6: Influence of engineering and true stress controlled experiments on ratcheting strain accumulation in (a) 304LN and (b) SA333 Gr.6 steels

The fatigue life of both the materials was more during true stress controlled experiments than under engineering stress control. The reasons for the decrease fatigue life during engineering stress control experiments were thought to be due to (i) rapid accumulation of ratcheting strain than under true stress control, (ii) a continuous increase in the actual true stress on the specimen, (iii) instability and necking produced due to large reduction of cross-sectional area. On contrary, during true stress controlled experiments, failure always occurred by initiation and growth of fatigue cracks. All these observations are true for a positive mean stress. However, when the mean stress is negative, the fatigue life increases during engineering stress controlled situation when compared to that during true stress control. The reason for this anomaly is that the presence of compressive mean stress drives the ratcheting strain in compressive direction (a case contrary to the increasing true stress) as a result of which true stress amplitude reduces with progressive cycling, leading to an increase in life. The comparison brings forth the inadequacy in engineering stress controlled experiments to understand the ratcheting behaviour of materials, specifically involving large strains and suggests true stress control experiments for test conditions that are expected to produce large strain accumulation. The results show that both the methods produce almost identical strain accumulation for the initial few cycles. It is only with the progressive cycles, the strain accumulation by the two methods is largely different. The assumption (as in many investigations available in literature) that for small magnitudes of ratcheting strain accumulation the investigation employing engineering stress control ignoring the dimensional changes in the specimen seems to be logical. However, it is very difficult to specify a cycle/strain limit below which an engineering stress controlled test would yield acceptable results. Ratcheting strain evolution in the two modes of experiments depends up on the material characteristics and loading conditions. For these reasons, it would be a good practice if the ratcheting response is investigated under true stress control irrespective of the expected magnitude of strain accumulation.

CONCLUSIONS

Based on the present investigation on SA333 C-Mn steel and 304LN stainless steel the following conclusions can be made:

Cyclic hardening/softening is not only dependent on material but also on the loading condition and loading history. Stress amplitude alternations in pure LCF are strongly depending upon applied strain amplitude. Increment of linear portion of the hysteresis loops with cycling is responsible for cyclic hardening in SA333 C-Mn steel and 304LN stainless steel.

Both tensile and cyclic pre-straining produced identical memory effect. The prior history memory alerted the hardening/softening behaviour. However, the prior history memory disappeared after sometime.

SA333 C-Mn steel and 304LN stainless steel shows non Masing behaviour (strain range effect). Non Masing behaviour is due to change of the linear portion of hysteresis loops with strain amplitude.

Mean stress is relaxed with cycles in asymmetric strain cycling. Pre-straining followed by LCF and mean stress relaxation shows similar kind of material response.

True stress controlled ratcheting test procedure is recommended for evaluating materials ratcheting response over engineering stress controlled experiments. True stress controlled experiments show an increase in fatigue life than during engineering stress controlled experiments.

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