BEHAVIOR OF 304L STAINLESS STEEL UNDER UNIAXIAL LOADING AND EFFECT OF THE MEAN STRESS ON THE RATCHETING BY SIMULATION USING CHABOCHE MODEL

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The aim of this paper is the study of the behavior of 304L austenitic stainless steel, under uniaxial cyclic loadings. In addition, the effects of loading rate, mean stress and stress amplitude on the ratcheting behavior are investigated. Two kinds of boundary conditions were selected in all simulations tests, the first with imposed deformation showing a hardening of the material and the second with imposed stress showing the effect of the average stress on the ratcheting phenomenon which corresponds to an excessive deformation, cycle after cycle and leads to an incremental damage of the structure. The elastoplastic model of Chaboche is used, validated by a large test data base using the "ZéBulon" finite element software.

Keywords: Ratcheting; cyclic loading; uniaxial; hardening; simulation; mean stress; intensity.

1. Introduction

The study of the cyclic behavior of materials has been a great success with the development of computer tools more and more powerful. This development has created a growing demand in the scientific community for the accuracy of numerical simulations and in computing time. A significant effort has recently been made in the development of behavioral models able to simulate the service life of structures subjected to complex cyclic stresses. Numerous works represent the state of the art in the field of cyclic behavior of metallic materials; see Abdel-Karim, [1].

The ratcheting phenomenon is defined as accumulation of plastic strain with the application of cyclic load characterized by a constant stress amplitude with a

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nonzero mean stress. With a lot number of load cycles applied, the whole strain become so huge that the original shape of the structure is deformed, who which results in an unusable structure [2-4].

Ratcheting is an important element introduced in designing structural components. Ratcheting with uniaxial cyclic loading with nonzero mean stress is denoted as uniaxial ratcheting, which is the most fundamental and has been studied in many works for 304L stainless steels, like Kang and Gao [5] and Kang et al. [7]; Djimli et al. [6], Taleb and Hauet [8], Chaboche [9], and Krempl [10].

When the component is subject to asymmetrical loading, material can break since of its unacceptable ratcheting deformation. For that it is necessary to evaluate the ratcheting behavior of material because it is one of the most important factors that should be considered in the structural design [11-16]. The impact of diverse loading paths on the ratcheting mechanism was also carefully observed. Elements like the mean stress, stress amplitude, strain amplitude and their histories were revealed to relate to the ratcheting strain. For the material model, the nonlinear Chaboche model can provide more accurate results in many cases involving cyclic loading [17-21].

In the present work, therefore, the uniaxial ratcheting characteristics of 304L stainless steel in cyclic tension-compression at room temperature are considered. The effects of loading rate mean stress and stress amplitude on the ratcheting behavior of 304L stainless steel are discussed.

2. Material model

The choice of the appropriate model of the material behavior is considered as a basic step for the description of the hardening produced during the cyclic loading. This operation allows us, to properly simulate the response of the material during use.

The Chaboche model with isotropic and kinematic nonlinear hardening [9], able to reproduce various behaviors of the material (elastic shakedown, plastic shakedown and ratchet effect) was used in this work. The loading surface of the material is described by a load function *f* with von Mises yield criteria given in Eq. (1), that depends on the stress tensor σ, the elastic limit of the material σ_y, of the isotropic work hardening variable R and nonlinear kinematic hardening variables $\left(\underline{X}\right)$.

$$f = J\left(\underline{\sigma} - \underline{X}\right) - R - \sigma_{yi}, \tag{1}$$

where *J* is the second invariant of the tensor deviator of stress.

The variable of isotropic hardening R increases with the rate of cumulated plastic deformation and its law of evolution is written:

$$dR = b\left(Q - R\right) dp, \tag{2}$$

with Q and b constants of the material which have the effect of introducing progressive hardening or softening.
The variables of nonlinear kinematic hardening are contained in the tensor $\underline{X}$ whose evolution is described by the relation:

$$d\underline{X} = \frac{2}{3}C(p)\,d\underline{\varepsilon}^{p} - \gamma(p)\,\underline{X}\,dp \tag{3}$$

where C and γ are kinematic hardening parameters and $d\underline{\varepsilon}^{p}$ plastic strain.

In relation (3) dp is the increment of the cumulated plastic strain.

$$dp = \left[\frac{2}{3}d\underline{\varepsilon}^{p} : d\underline{\varepsilon}^{p}\right]^{1/2} \tag{4}$$

The parameters of the Chaboche model used in this study are those obtained from the works of Djimli et al. [6] using the ZéBulon finite element program [22], see Table 1. Fig.1 shows a superposition of the numerical results obtained with the ZéBulon code and the experimental ones obtained during the cyclic tests for a 304L steel.

Table 1

Mechanical properties and parameters of Chaboche model for 304L stainless steel [6]**.**

E [MPa]	ν [-]	σy [MPa]	b [MPa]	Q [MPa]	C [MPa]
206000	0.3	160	35	45	51200

We note that, E is the Young's modulus and ν is Poisson ratio.

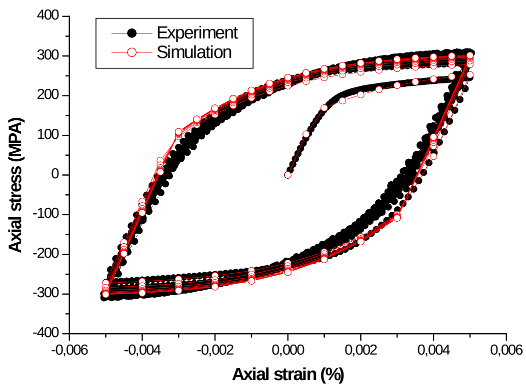


Fig. 1. Superposition of the experimental stabilized loop and simulation

3. Results and discussion

The main goal in this investigation is to study and examine in what way parameters as the mean stress and the amplitude stress influence the ratcheting behavior of 304L stainless steel material.

3. 1 Cyclic strain-controlled tests

Controlled strain tests under axial proportional loading provide information on hardening or cyclic softening of the material, [6]. The test consists in carrying out 10 controlled tension-compression cycles between ± 0.5%. The Fig. 2a represents the strain controlled as a function of time. However, Fig. 2b reveals hardening steel caused by the increase of the axial stress as a function of time. While Fig. 2c shows the variation of the stress as a function of the strain, it provides hysteresis loops.

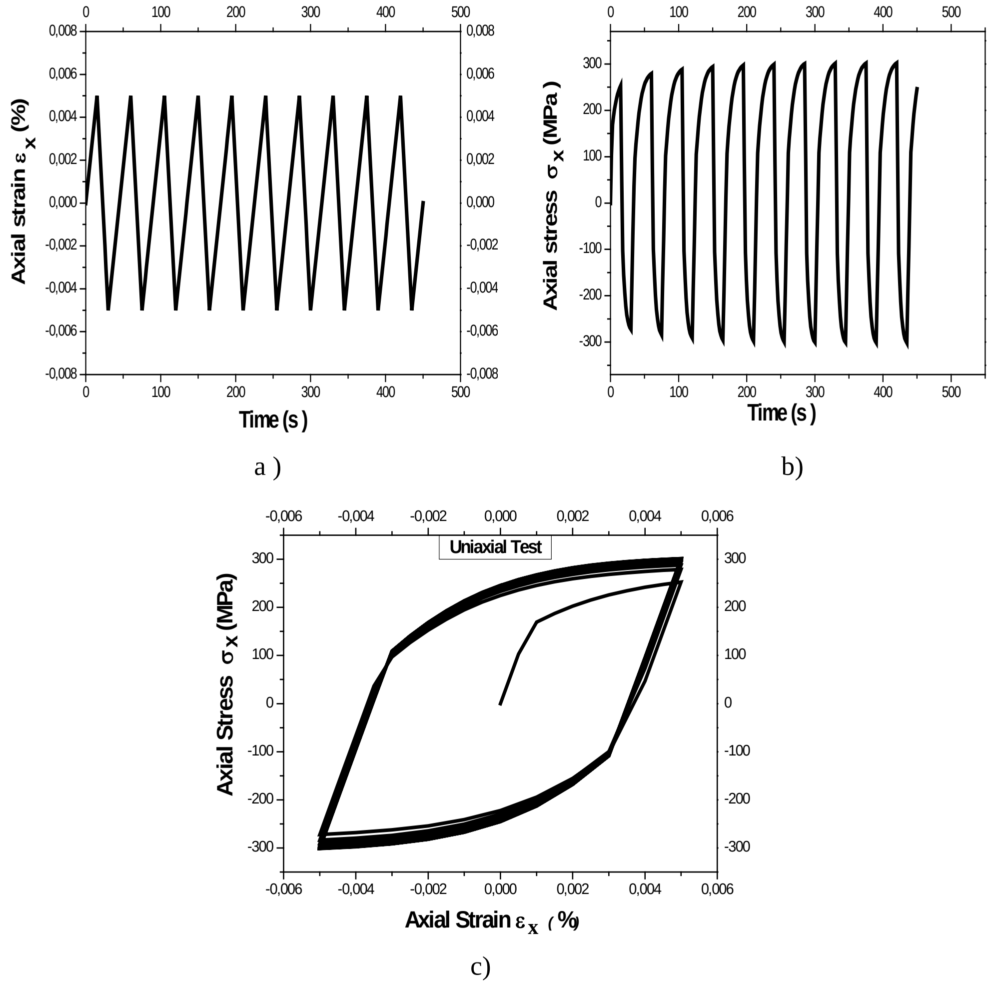


Fig. 2. Behavior of 304L steel under tension–compression cyclic loading: a) imposed strain,ic hardening, c) axial stress strain loops

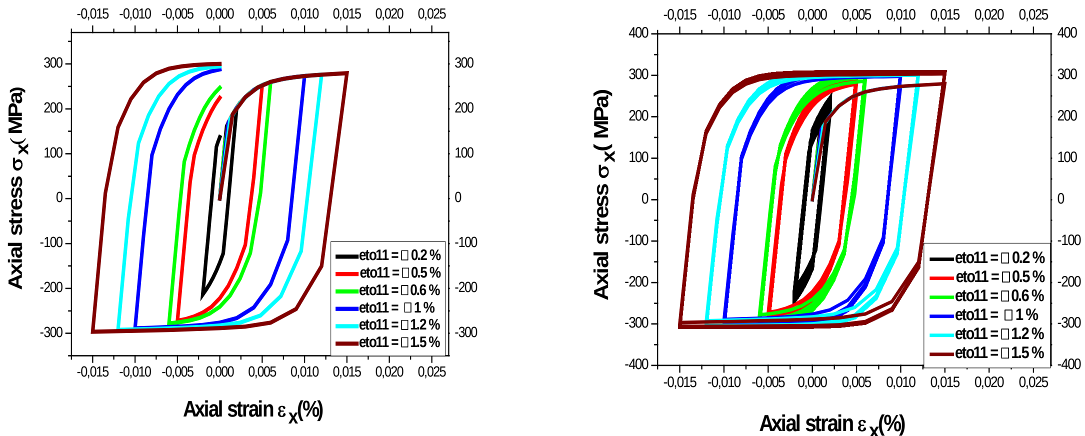
3.1.1 Effect of the progressive amplitude of the imposed strain

For the study of the progressive effect of the imposed strain (IS), tests were carried out by increasing strain amplitudes, see Table 2. The results of tests carried out with (IS) between two extreme values are showed in Fig. 3. The material is cyclically loaded with a uniaxial loading path (tension-compression). We note that the curves of hardening show a hardening behavior caused by the increase of the stress as a function of the number of cycles.

Table 2

Increasing strains amplitudes with the corresponding stresses amplitudes for a stabilized cycle

ε_x [%]	± 0.2	± 0.5	± 0.6	± 1	± 1.2	± 1.5
σ_x [MPa]	200	250	260	275	280	295



a) b)

Fig.3. Hysteresis curves of 304L stainless steel obtained from strain controlled tests at different strain ranges for: a) 1 cycle, b) 10 cycles.

3.2 Ratcheting tests

In the case of linear kinematic hardening with asymmetric imposed stress, the material exhibits an elastic shakedown behavior. The plastic shakedown is perceived when the kinematic hardening is non-linear and the alternating loading is symmetrical. In this case, the asymmetric loading causes an incremental strain called ratcheting, which depends mainly on the material parameters and the level of loading.

3.2.1 Effect of the average stress (Ratcheting 1D)

In order to analyze the ratcheting phenomenon under the effect of the average stress, we carried out two tests with imposed stress (see Table 3):

- H1: 50 cycles with symmetrical tension-compression stress (300 MPa - 300 MPa).
- H2: 50 cycles with non-symmetric tension-compression stress (300 MPa -100 MPa) around a mean stress 100 MPa, in the axial direction.

The average stress is the source of the appearance of two phenomena, Fig. 4:

1. The first one is a plastic shakedown caused by the symmetry of the imposed amplitude of stress, producing the rupture of the structure by alternating low cycle plasticity, designated by the term of oligocyclic fatigue.
2. The second one represents a progressive strain due to the asymmetry of the amplitude of the imposed stress causing unstable behavior over time.

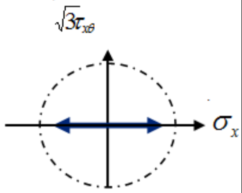
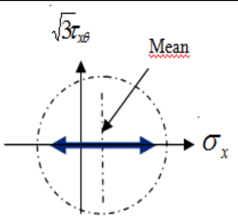
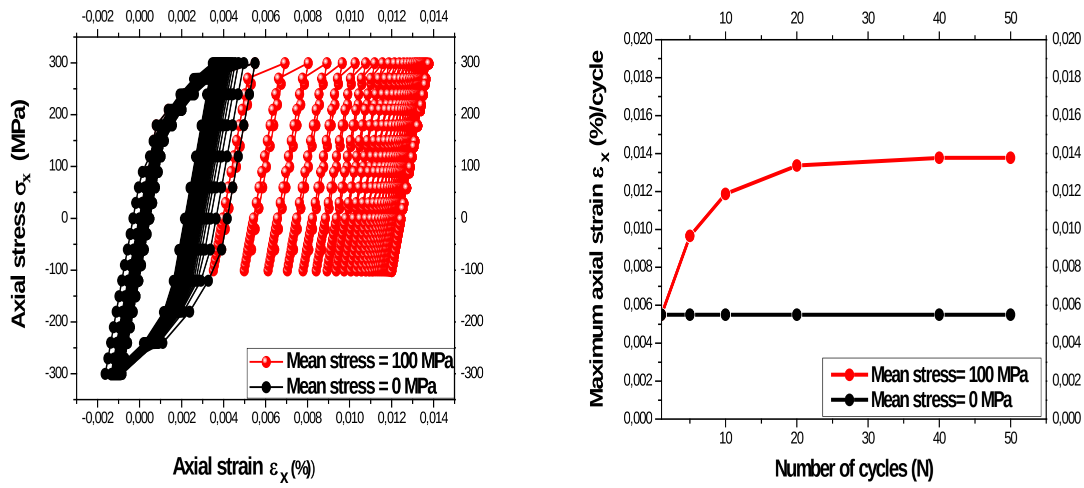
Loading path	Ref	Loading history	σ_{max} [MPa]	σ_{min} [MPa]	$\sigma_{mean} = \frac{\sigma_{max}+\sigma_{min}}{2}$ [MPa]	$\sigma_a = \frac{\sigma_{max}-\sigma_{min}}{2}$ [MPa]	$R = \frac{\sigma_{min}}{\sigma_{max}}$
	Fig.4	H1	+ 300	-300	0	300	-1
		H2	+ 300	-100	100	200	- 0.33

Table 3

Stories, loading path, imposed stress and load report

Fig. 4a is divided in two curves; the first aims to test 304L Stainless Steel under asymmetrical stress-controlled cycling under stress amplitude of 200 MPa, and mean stress of 100 MPa, it can be seen the hysteresis loops which are not closed at the beginning, this result confirms the ratcheting response of the material, (red color). While the second (black color) presents the test carried out under a stress amplitude of 300 MPa, and zero mean stress, in which the steel exhibits plastic shakedown and will fail after a finite number of load cycles due to low-cycle fatigue and provide closed stress–strain hysteresis loops. The evolution of the axial strain peaks versus the number of cycles of the two phenomena (ratcheting and plastic shakedown) is given in Fig. 4b where the evolution of ratcheting under non zero mean stress is more important compared to ratcheting under zero mean stress.



a) b)

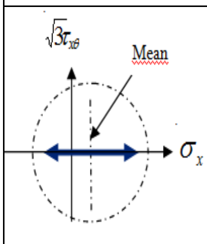
Fig. 4. The effect of the mean stress on the ratcheting, a) illustration of plastic shakedown and ratcheting phenomena of 304L steel, b) evolution of the maximum axial strain versus the number of cycles.

3.2.2 Effect of intensity of mean stress on the ratcheting

The main objective of the simulation tests as shown in Fig. 5a, Fig. 6a, Fig. 7a, Fig. 8a relative to the four loading histories, see Table 4, is to investigate the importance of intensity of mean stress σ_{mean} in the cyclic behavior of the 304L. The stress–strain curves illustrate the plastic behavior indicated by the hysteresis loops with progressive cycles. However, Fig. 5b, Fig. 6b, Fig. 7b and Fig. 8b give the results of the test where the maximum axial strain reaches different rates at 200 cycles.

Table 4

Stories, loading path, increasing average stress and load report

Loading path	Ref	Loading history	Number of cycles	$\sigma_{\max}$ [MPa]	$\sigma_{\min}$ [MPa]	$\sigma_{mean}=\frac{\sigma_{\max}+\sigma_{\min}}{2}$ [MPa]	$\sigma_a=\frac{\sigma_{\max}-\sigma_{\min}}{2}$ [MPa]	$R=\frac{\sigma_{\min}}{\sigma_{\max}}$
	Fig.5	H1	200	+ 300	-200	50	250	-0.66
	Fig.6	H2		+ 300	-150	75	225	-0.5
	Fig.7	H3		+ 300	-100	100	200	-0.33
	Fig.8	H4		+ 300	-50	125	175	-0.16

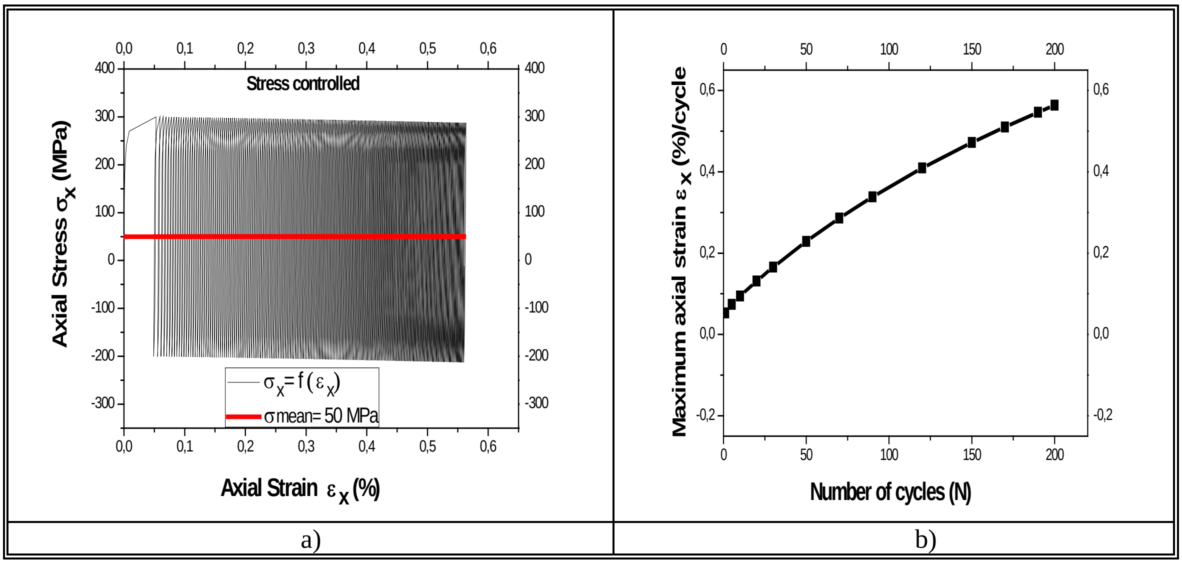


Fig.5. Result of ratcheting 1D under constant mean stress (σ_{mean} = 50MPa), a) axial stress–strain loops, (b) axial strain peaks versus the number of cycles.

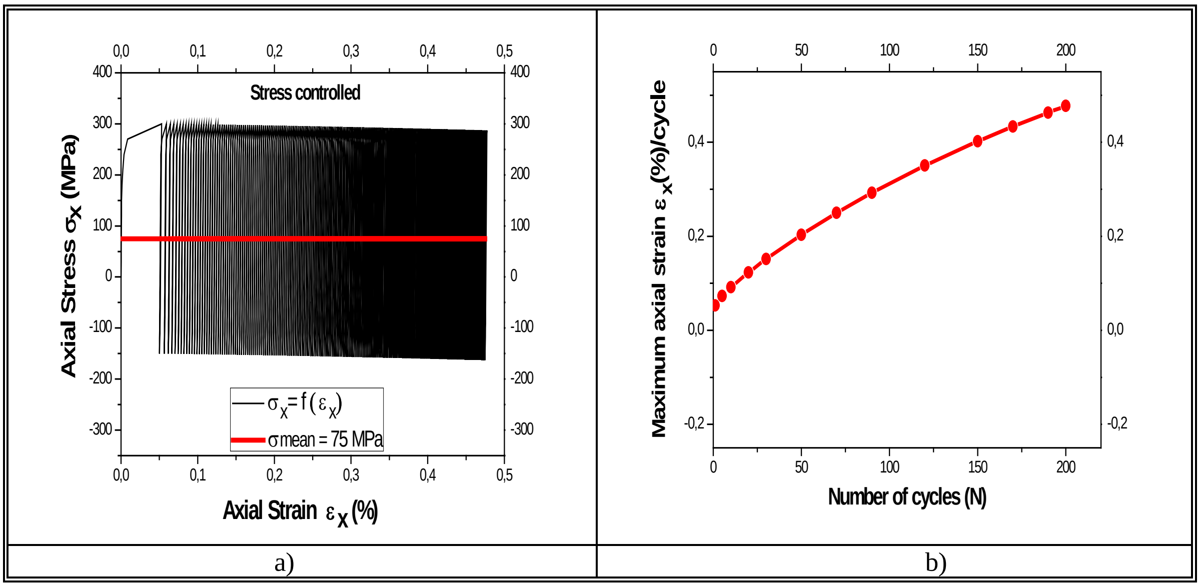


Fig.6. Result of ratcheting 1D under constant mean stress (σ_{mean} = 75MPa), a) axial stress–strain loops, (b) axial strain peaks versus the number of cycles.

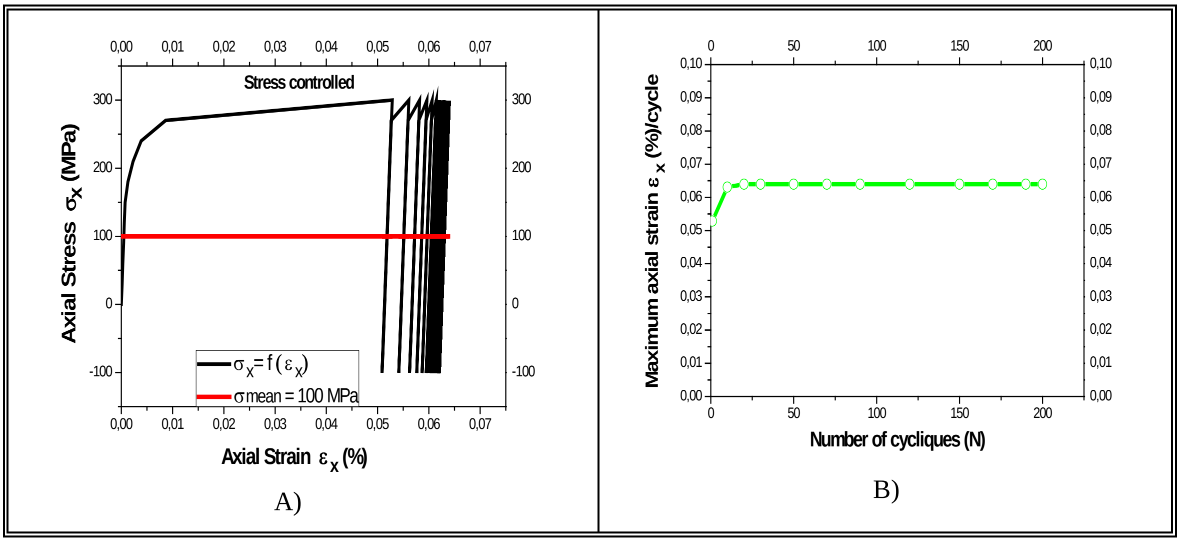


Fig.7. Result of ratcheting 1D under constant mean stress (σ_{mean} = 100MPa), a) axial stress–strain loops, (b) axial strain peaks versus the number of cycles.

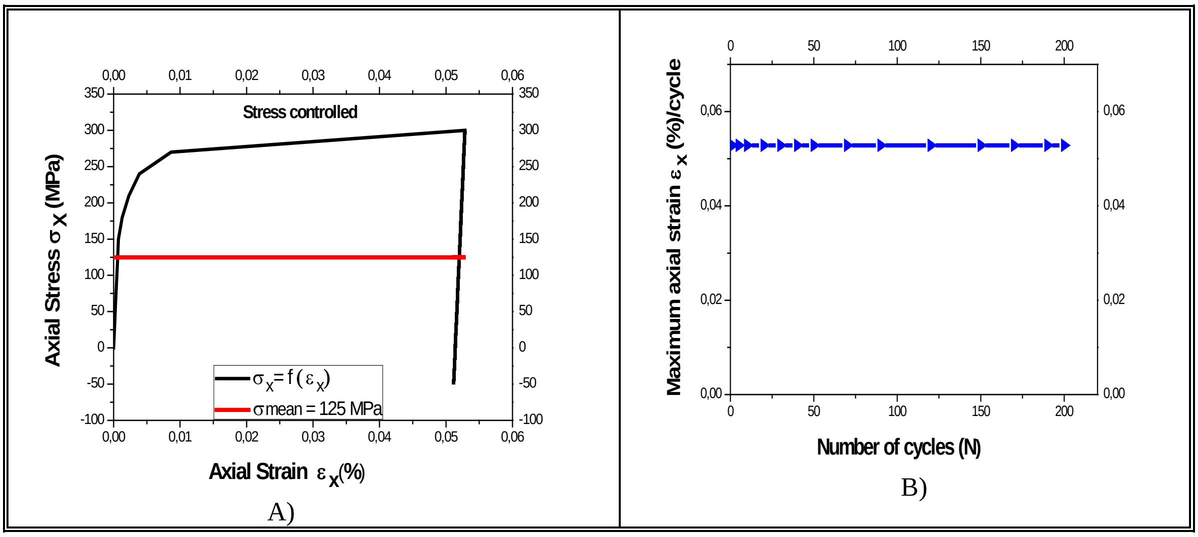


Fig.8. Result of ratcheting 1D under constant mean stress (σ_{mean} = 125MPa), a) axial stress–strain loops, b) axial strain peaks versus the number of cycles.

The obtained axial strain peaks versus the number of cycles are given in Fig. 9, as the mean stress is considered as one of the parameters favoring the appearance of incremental plastic strain, the rates of ratcheting from the four loading histories, are so different when they have the same loading path under various mean stresses.

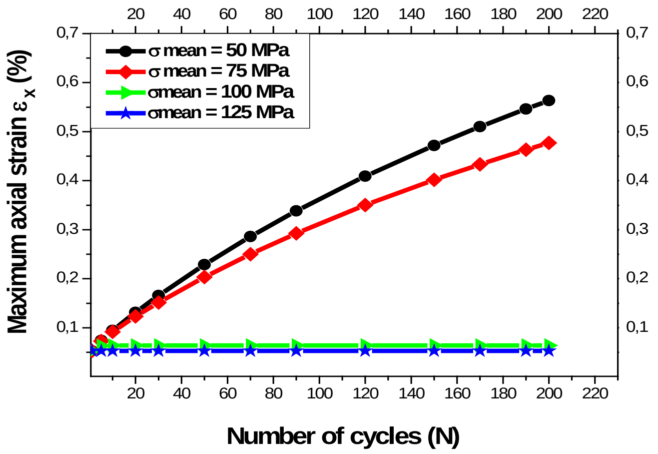
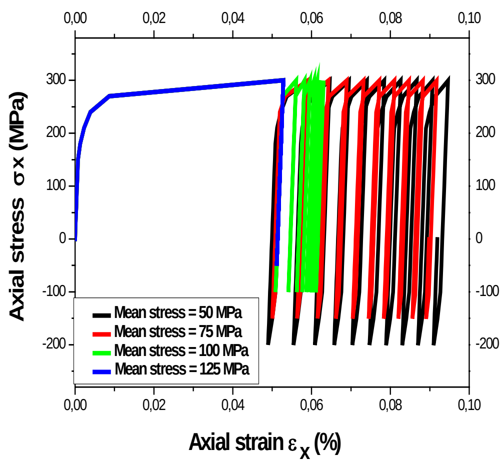
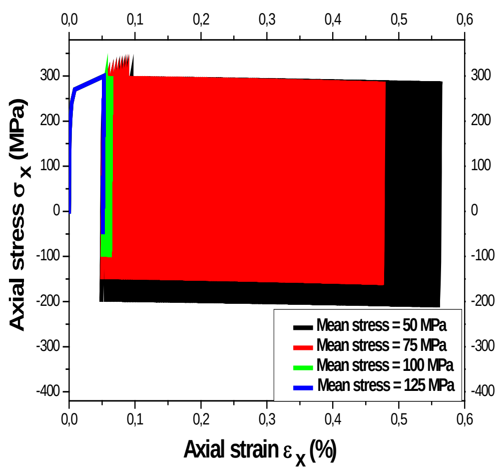


Fig.9. Axial strain ratcheting versus the number of cycles from stress-controlled simulations under various mean stresses.

In order to understand the ratcheting sensitivity to the different mean stress and different stress amplitude, Fig. 10 summarizes the effects of the mean stress on uniaxial ratcheting. When the mean stress is decreased, stress amplitude and ratcheting strain increased. It can be found that the mean stress and stress amplitude have a great influence on the uniaxial ratcheting strain.



a)



b)

Fig.10. Superposition of four loads history in the classical tension–compression ratcheting tests under various mean stresses, a) Ratcheting 1D for 10 cycles, b) Ratcheting 1D for 200 cycles.

4. Conclusion

This paper aims to study the behavior of the 304L stainless steel stainless steel under stress/strain controlled conditions in axial direction. The cyclic hardening/softening behavior of metals under strain control has also been investigated.

A large part of the work is devoted to understanding the role of mean stress on the ratcheting and is divided in two separate investigations:

The first is devoted to study the effect of the null and non-zero mean stress in the case of the plastic shakedown and ratcheting phenomena.

The second is devoted to the testing of the material under four asymmetric stress controlled cycling. The ratcheting is influenced by the intensity of the mean stress and amplitude stress of the loading history. Axial strain ratcheting from these four tests is compared by plotting the maximum peaks versus the number of cycles. The mean stress has a great influence on the uniaxial ratcheting strain. Obviously, the decrease of mean stress will result in the rapid increase of the uniaxial ratcheting strain and when the stress amplitude is increased the ratcheting strain increased rapidly.

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