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Influence of stress level on uniaxial ratcheting effect and ratcheting strain rate in austenitic stainless steel Z2CND18.12N

Xiaohui Chen *[1,2], Xu Chen [3] and Haofeng Chen [4]

[1] *School of Control Engineering, Northeastern University, Qinhuangdao 066004, China*
[2] *School of Mechanical Engineering & Automation, Yanshan University, Qinhuangdao, 066004, China*
[3] *School of Mechanical Engineering & Automation, School of Tianjin University, Tianjin, 300072, China*
[4] *Department of Mechanical & Aerospace Engineering, University of Strathclyde, G1 1XJ, UK*

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Abstract. Uniaxial ratcheting behavior of Z2CND18.12N austenitic stainless steel used nuclear power plant piping material was studied. The results indicated that ratcheting strain increased with increasing of stress amplitude under the same mean stress and different stress amplitude, ratcheting strain increased with increasing of mean stress under the same stress amplitude and different mean stress. Based on least square method, a suitable method to arrest ratcheting by loading the materials was proposed, namely determined method of zero ratcheting strain rate. Zero ratcheting strain rate occur under specified mean stress and stress amplitudes. Moreover, three dimensional ratcheting boundary surface graph was established with stress amplitude, mean stress and ratcheting strain rate. This represents a graphical surface zone to study the ratcheting strain rates for various mean stress and stress amplitude combinations. The graph showed the ratcheting behavior under various combinations of mean and amplitude stresses. The graph was also expressed with the help of experimental results of certain sets of mean and stress amplitude conditions. Further, experimentation cost and time can be saved.

Keywords: uniaxial ratcheting; cyclic loading; least square method; zero ratcheting strain rate; three dimensional ratcheting boundary surface

1. Introduction

Ratcheting effect, one of the low cycle fatigue responses, was defined as the accumulation of plastic strain with cycles. Ratcheting strains at the different stages were investigated at various types of loading cycles. The curve of the ratcheting strain could be divided into three stages, as shown in Fig. 1. In the primary stage, the ratcheting strain increased rapidly since the plastic strain accumulated fast. In the second stage, the ratcheting strain increased steadily with a constant rate. In the last stage, the ratcheting strain increased rapidly because of the crack initiation. Finally, the specimen failed as a result of crack propagation.

In the assessment of nuclear class 1 pressure retaining components it was the assessment of ratcheting which was the main source of uncertainties when using elastoplastic analysis procedures. This should be taken seriously since on a regular basis ratcheting was the failure mode which is crucial for the design of nuclear component and piping system. It was therefore, of great importance to clarify which types of constitutive models were suitable and how the model parameters should be calibrated in order to give reliable results when assessing ratcheting. In recent decades, ratcheting strain of metal materials was studied by many scholars. Ohno (1990, 1997) summarized ratcheting test of material and constitutive models. Kang (2008) also reviewed ratcheting test of material and constitutive models, meanwhile still presented some suggestions for the studies of ratcheting behaviour. Yu *et al*. (2012) carried out monotonic uniaxial tensile tests at different strain rates and the reversed strain cycling test for Z2CND18.12N steel. Experimental results showed the characteristics of rate-dependence and cyclic hardening of Z2CND18.12N austenitic stainless steel at room temperature, respectively. Thus, a visco-plastic constitutive model incorporated with isotropic hardening was developed based on the Ohno–Wang kinematic hardening rule to describe the uniaxial ratcheting behavior of Z2CND18.12N steel under various stress-controlled loading conditions. Liang (2014) studied uniaxial tensile and ratcheting-fatigue behaviour of the nuclear power pipeline steel (Z2CND18.12N) with different thermal aging times. The results indicated that the thermal aging process changed the ratcheting behaviour and ratcheting-fatigue of the material. All researches observed that ratcheting strain would decrease fatigue life of materials/structures, and even lead to catastrophic failure of the structures. Z2CND18.12N austenitic stainless steel was made for primary coolant circuit auxiliary pipes, ratcheting effect of which was studied by Chen (2015). The results indicated that the effect of internal pressure and bending on ratcheting strain was prominent.

Pham *et al*. (2013) observed the results from experiments on the material 316L, which showed the evaluation of stress amplitude as a function of the number of cycles at three different strain amplitudes at room

∗Corresponding author, Ph.D., Professor,
E-mail: chenxh@neuq.edu.cn

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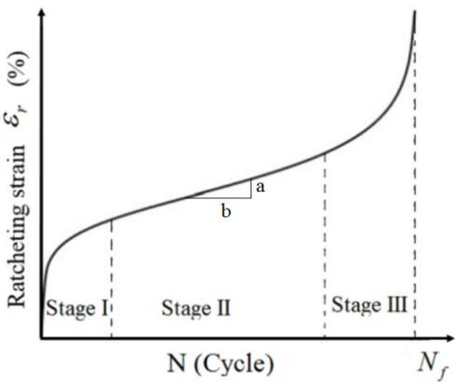


Fig. 1 Schematic triphasic trend of ratcheting strain over a stress cycles

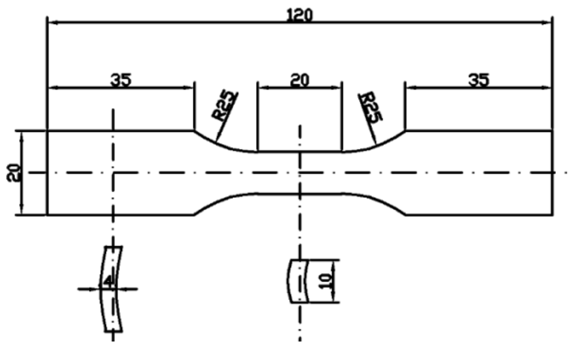


Fig. 2 Plate tension specimen

Table 1 Loading conditions of uniaxial ratcheting test

Material	Mean stress σ_m, MPa	Stress amplitude $\Delta\sigma/2$, MPa	Ratcheting strain rate, %, $\times 10^{-3}$
Z2CND18.12N	150	150	0.219
		175	0.876
		200	1.438
	150	150	1.971
	175		2.259
	200		4.929

temperature. All tests showed initial cyclic hardening followed by cyclic softening material behaviour after a rather large number of cycles. It was also observed that the cyclic hardening was more significant for larger strain ranges. Facheris *et al*. (2013) investigated the micro-structural level of AISI 316L stainless steel during the low fatigue experiments. It was observed at micro level that the density of dislocations induced in channels were higher when a cyclic test was performed with a mean stress in comparison to when a test was performed with zero mean stress. It was hypothesized that this effect can explain the change in material hardening and hence partly also explain the material ratcheting behavior. Sarkar *et al*. (2016) studied the effect of mean stress and stress amplitude on the cyclic life under elevated temperature (823-923 K) ratcheting of 316LN austenitic stainless steel. Constant life Haigh diagrams have been generated, using different combinations of stress amplitude and mean stress. Strong influence of dynamic strain aging (DSA) was found at 823 K which affected the mode of deformation of the material in comparison with 923 K.

Sarkar *et al*. (2017) investigated the effect of low cycle fatigue, high cycle fatigue, creep and their interactions during combined cycling at high temperature (923K) in a 316LN stainless steel. Taleb (2013) carried out two current austenitic stainless steels 304L and 316L tests under cyclic stress and strain control at 350℃. Under stress control ratcheting seemed very small under proportional as well as non-proportional stress control. The elastic shakedown steady state exhibited by both materials may be explained by their capabilities to develop very significant cyclic hardening at 350℃.

In this study, uniaxial ratcheting behaviour of Z2CND18.12N austenitic stainless steel for primary coolant circuit auxiliary pipes was analysed. Meanwhile, zero ratcheting strain rate was proposed in order to prevent ratcheting behaviour.

2. Experiment specimens

Uniaxial ratcheting test of Z2CND18.12N austenitic stainless steel was carried out in this study. The chemical composition and mechanical properties of Z2CND18.12 austenitic stainless steel was given in references (Liang 2014, Chen 2015).

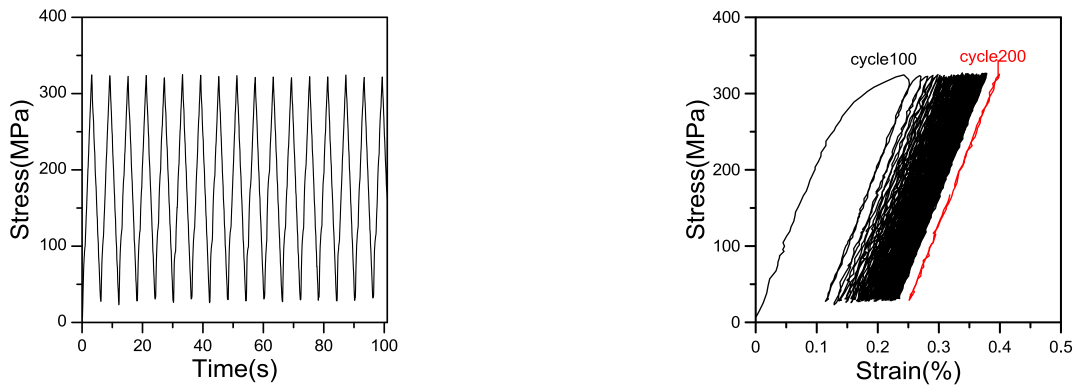
Table 1 gave uniaxial ratcheting test conditions of Z2CND18.12N austenitic stainless steel under mean stress and stress amplitude. Loading applying method was triangular wave, and loading control was employed in the ratcheting tests. In this study, ratcheting strain was the average value of the sum of maximum strain $\varepsilon_{\max}$ and minimum strain $\varepsilon_{\min}$ in each cyclic hysteresis curve, namely

$$\varepsilon_r = \left(\varepsilon_{\max} + \varepsilon_{\min}\right) / 2 \qquad (1)$$

3. Experimental results and discussions

Fig. 2(a) showed an example of schematic loading path for uniaxial ratcheting test under mean stress 175 MPa, stress amplitude 150 MPa and stress rate 100 MPa/s. The relationship of the corresponding stress and strain was given in Fig. 2(b). It was found that the hysteresis loop in initial cycles was not closed. This phenomenon was held in the subsequent cycles, but not obvious. The above process was corresponding to plastic strain accumulation, namely ratcheting effect. Cyclic damage in the material increased with an increase in strain acc umulation that was illustrated by the hysteresis loop shifting towards the large plastic strain amplitude; due to this ratcheting phenomenon dislocation density in samples increased.

Fig. 3 gave the uniaxial ratcheting evolution rule of Z2CND18.12N austenitic stainless steel under mean stress 175 MPa and stress amplitude 150 MPa. It was shown in Fig. 3 that ratcheting strain was accumulated quickly in



(a) Stress control diagram (b) Stress-strain relationship

Fig. 2 Stress control and stress vs strain curve

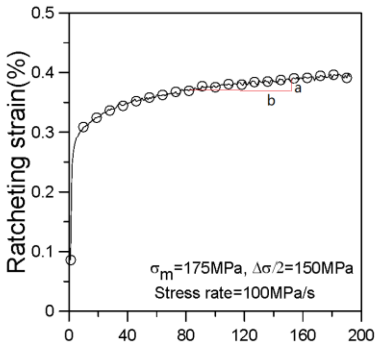
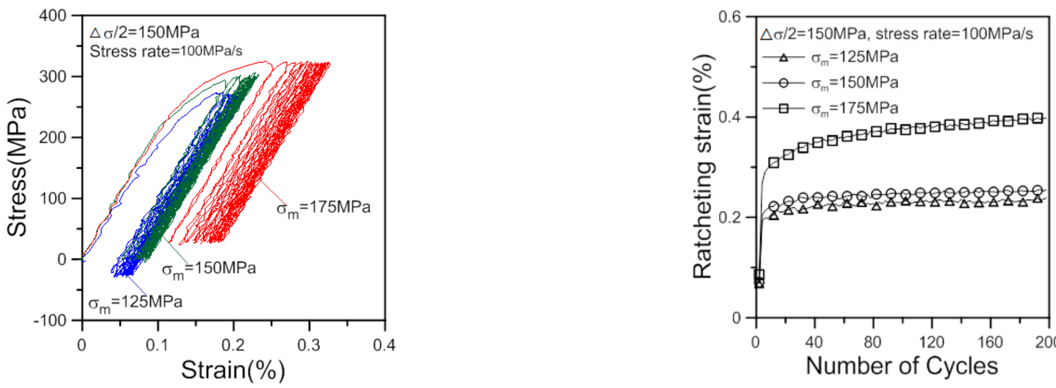


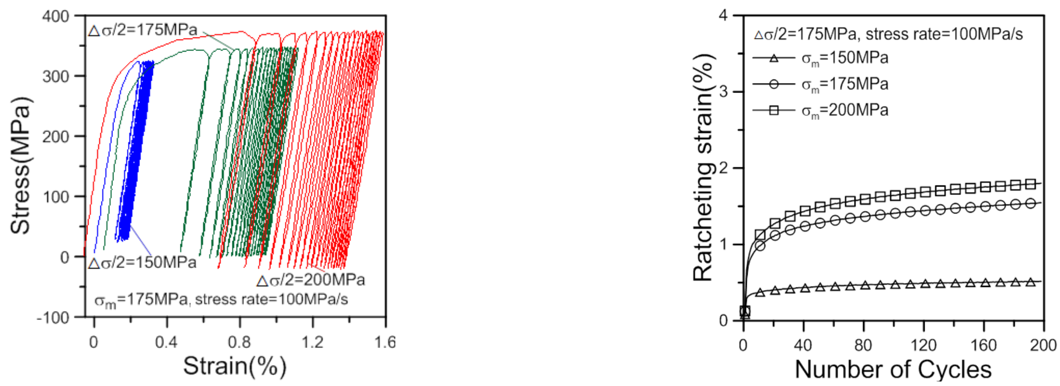
Fig. 3 Ratcheting strain

initial cycles, and ratcheting strain rate was also very large.The cumulative velocity of ratcheting strain with cycling became slowly, and then ratcheting strain rate also gradually decrease. The process of ratcheting effect can be evaluated in two stages, in stage I ratcheting strain rate decreased with increase in the loading cycles. In stage II ratcheting strain rate reached a constant with further increase in cycles and during this stage only ratcheting strain keep on growing at a steady rate. In this study, all experiments did not proceed to the third stage and was terminated.

Fig. 4 showed uniaxial ratcheting evolution rule of Z2CND18.12N austenitic stainless steel under constant



(a) (b)



(c) (d)

Fig. 4 Uniaxial ratcheting behavior with the constant amplitude of 150 MPa and175 MPa under different mean stresses

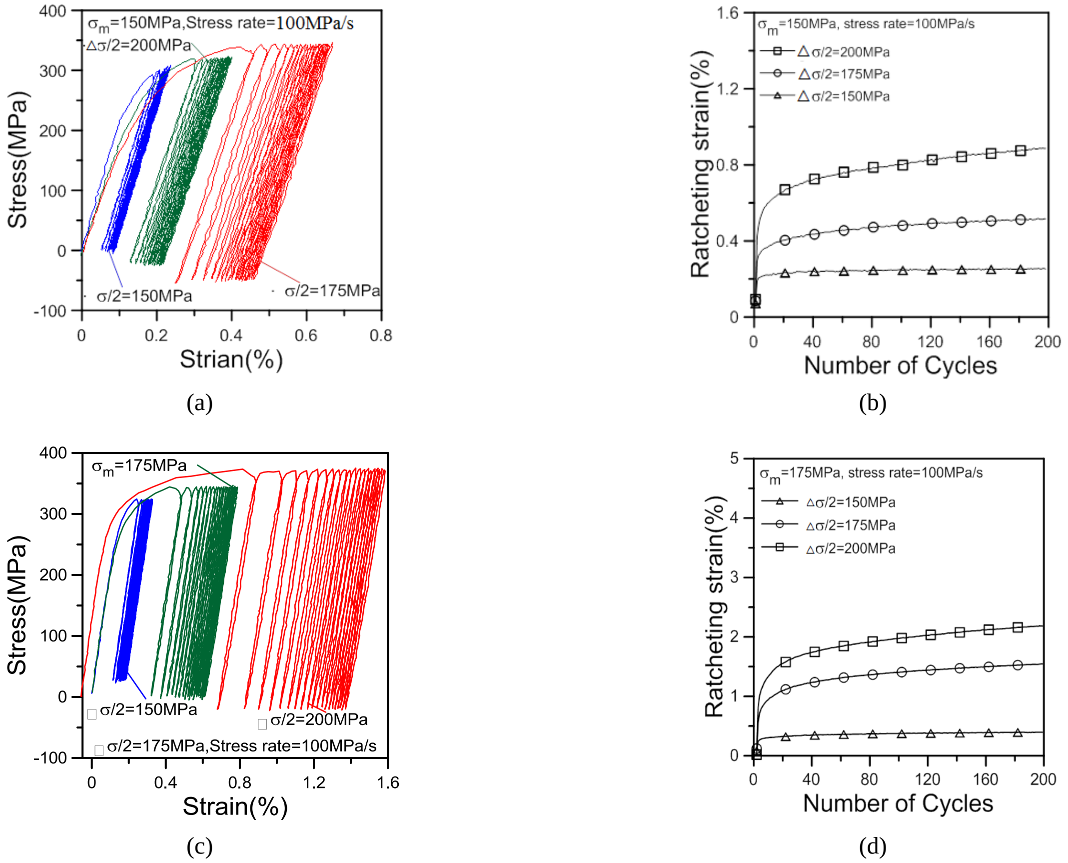


Fig. 5 Uniaxial ratcheting tests with the constant mean stress of 150 MPa and 175 MPa and different stress amplitudes

stress amplitude 150 MPa and 175 MPa, respectively.. It was found that ratcheting strain and ratcheting strain rate increased with the increasing of mean stress. Ratcheting strain rate decreased with the increasing of number of cycles.

Uniaxial ratcheting evolution rule of Z2CND18.12N austenitic stainless steel under constant mean stress 150 MPa and 175 MPa was shown in Fig. 5, respectively. It indicated ratcheting strain increased with the increasing of stress amplitude. Ratcheting strain rate decreased with the increasing of number of cycles.

4. Ratcheting strain rate and ratcheting boundary

4.1 Relationship of mean stress, stress amplitude and ratcheting strain rate

This study focused only on ratcheting behaviour of Z2CND18.12N austenitic stainless steel at stage II due to uniaxial loading. Ratcheting strain rate $\dot{\varepsilon}_r$ was calculated using the tangent of ratcheting strain and loading cyclic graph as given in Fig. 6.

$$\dot{\varepsilon}_r = Angular\ tangent\left(a/b\right) = d\varepsilon_r / dN \tag{2}$$

where, the parameters *a* and *b* were shown in Figs. 1 and 3. *N* represented number of cycles.

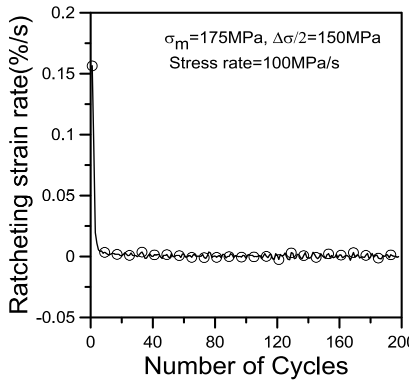


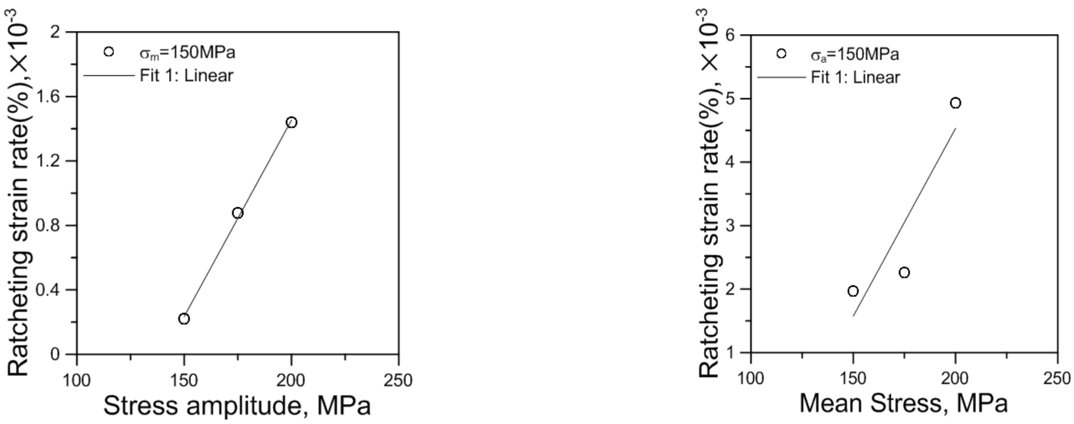
Fig. 6 Ratcheting strain rate

According to Eq. (1), ratcheting strain rate of Z2CND18.12N austenitic stainless steel under different mean stress and stress amplitude was calculated. Fig. 7(a) showed the ralationship of ratcheting strain rate under constant mean stress 150 MPa and stress amplitude. The correlation between ratcheting strain rate under constant stress amplitude150 MPa and mean stress, as shown in Fig. 7(b).

Based on least square method, Eq. (3) was used to regress Fig. 7.

$$y = mx + c \tag{3}$$

Table 2 listed the slope and vertical intercept of Eq. (3).



(a) (b)

Fig. 7 (a) Ratcheting strain rate vs. stress amplitude at constant mean stress of 150 MPa; (b) Ratcheting strain rate vs. mean stress at constant stress amplitude of 150 MPa

Table 2 Slope, intercept, mean stress and stress amplitudhpge values at zeros ratcheting strain

Material	Figure No.	Slope, *m*	Intercept, *c*	Zero ratcheting strain rate	
				Mean stress	Stress amplitude
Z2CND18.12N	Fig. 7(a)	0.0244	-3.422	150	140.367
	Fig. 7(b)	0.0592	-7.298	123.382	150

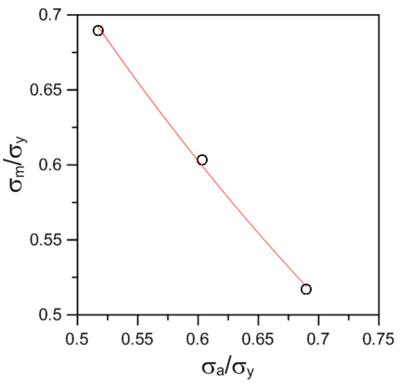


Fig. 8 Mean stress and stress amplitude relationship at yield stress of 290 MPa

According to Eq. (2), when ratcheting strain rate was zero, the corresponding mean stress and stress amplitude was calculated, as listed Table 2.

4.2 Ratcheting boundary

Ratcheting behavior of materials was generated under cyclic stress with non-zero mean stress. In other words, the effect of mean stress and stress amplitude on ratcheting effect was prominent. Therefore, the relationship of the ratio of stress amplitude and yield stress and the ratio of mean stress and yield stress was given in Fig. 8.

It was shown in Fig. 8 that the curve between σ_m/σ_y and σ_a/σ_y was exponential realtionship. Thus, the exponential realtionship was assumed as Eq. (4).

$$F(x) = C \cdot e^{kx} \quad (4)$$

Table 3 Values of the exponential equation constants in mean and amplitude stress relation

Material	$F(x) = C \cdot e^{kx}$	
Z2CND18.12N	Constant *C*	Constant *k*
	1.640	-1.669

where, the parameters *C* and *k* were constants.

4.3 Three dimensional ratcheting response surface and the ratcheting boundary

Ratcheting strain rate with constant mean stress and varying stress amplitude and with constant stress amplitude and varying mean stress of Z2CND18.12N austenitic stainless steel was indicated in Fig. 9, which was called as three dimensional ratcheting boundary surface. The mathematical equation used to generate this three-dimensional surface was as follows.

$$\dot{\varepsilon}_r = \left(m_1\sigma_m + m_2\sigma_a + c_1 + c_2\right)/2 \quad (5)$$

where, σ_m represented mean stress, σ_a represented stress amplitude. The parameters m_1 and m_2 were the slope of stress amplitude and ratcheting strain rate with constant mean stress and mean stress and ratcheting strain rate with constant stress amplitude, respectively. The parameters c_1 and c_2 were the vertical intercept of stress amplitude and ratcheting strain rate with constant mean stress and the vertical intercept of mean stress and ratcheting strain rate with constant stress amplitude, respectively. Fig. 9 indicated

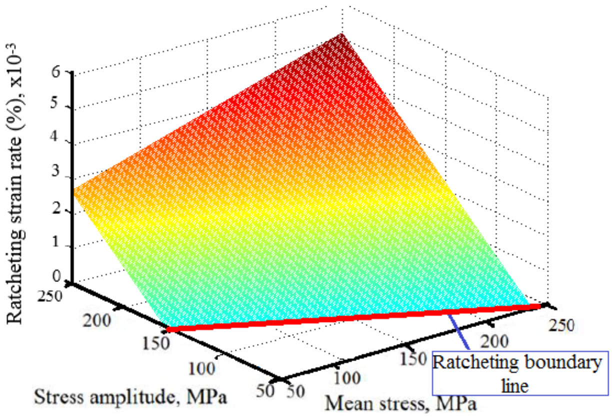


Fig. 9 Three dimensional ratcheting response surface

an irregularly inclined surface. Thus, the respective for different mean stress and stress amplitude graphically was observed. The three dimensional surface zone was constructed with certain boundary limits of maximum mean and amplitude stresses applied in the experiment. The boundaries can be increased by extending the trend line without changing the slopes and intercepts.

5. Conclusions

Uniaxial ratcheting test of Z2CND18.12N austenitic stainless steel was conducted in this study. The results was found to increase if the magnitude of mean stress increased with constant stress amplitude condition. The ratcheting strain increased with an increase in the magnitude of stress amplitude with constant mean stress state.

The process of ratcheting effect can be evaluated in previous two stages, in stage I ratcheting strain rate decreased with increasing of the loading cycles. In stage II ratcheting strain rate reached a constant with further increase in cycles and during this stage only ratcheting strain keep on growing at a steady rate. The study obsreved that ratcheting can be arrested and cannot be increased further if the material was loaded under zero ratcheting strain rate condition with specified mean stress and stress amplitude. Moreover, The three dimensional ratcheting boundary surface was built for Z2CND18.12N austenitic stainless steel to study the ratcheting behavior of the material under various combinations of mean and amplitude stresses. The surface graph was formulated with the help of experimental results of certain sets of mean and stress amplitude conditions. Multiple sets of stress combinations and their corresponding ratcheting rate can be obtained with some limited sets of experimental results. As a consequence, experimentation cost and time can be saved.

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