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Thermal–mechanical and isothermal fatigue of 304L stainless steel under middle range temperatures

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ABSTRACT

The present study investigates the crack initiation in a 304L stainless steel under thermal fatigue using volume element tests designed to assess the endurance to engineering crack initiation in real structures under middle range temperature and fairly large number of cycles. The inelastic cyclic strain is significant in most testing conditions for this alloy, even for long tests. Regarding tests, thermal–mechanical fatigue life is compared with low cycle fatigue tests under isothermal conditions. Noteworthy, throughout the different studied ranges of applied temperature cyclic behavior of the alloy has shown an initial hardening followed by a cyclic softening. In addition, no clear effect in lifetime for the high strain range has been discovered. In fact, when exposed to various increasing temperature levels, the material endurance tends to decreases for low strain range (correspond to high number of cycle). A different behavior in cyclic hardening tests is identified between the In-Phase thermal–mechanical fatigue tests and the Out-of-Phase tests at temperature levels ranges between 90 and 165 °C. In-Phase thermal–mechanical test increases lifetime with respect to the Out-of-Phase test. The fracture surfaces for all tested conditions are characterized by a fatigue striation.

1. Introduction

Thermal fatigue cracking is a widespread phenomenon that frequently affects a wide array of structures operating at high temperature conditions especially in the energy production area [1,2]. Thermal fatigue cracks have been discovered to occur in various components of nuclear power plants [3]. They particularly present in auxiliary loops of primary cooling systems in Pressurized Water Reactors (PWRs). A peak was reported to occur for instance in a reactor heat removal system of a certain plant. In most cases, these problems are likely due to mixing hot and cold water [1]. The progress witnessed in the mixing boundary edge between hot and cold water causes temperature fluctuations at the inner surface of the pipes (horizontal sections, t-junctions of connected lines to main loops). In most cases, the material concerned is 304L stainless steel base metal and welds [3–6]. As a matter of fact, this issue has constituted a subject matter dealt with a wide array of research work [2,6–9].

By means of an example, Fissolo et al. [10] have studied the thermal fatigue damage in parallelepipedic 316L specimen. In most cases, thermal fatigue endurance is often studied as a function of the specimen's temperature variation at its surface.

Other authors [3,11,12] performed thermal fatigue tests. For instance, they controlled the plastic strain range and the multi-axial excitations. Rau et al. [13] were interested in the experimental simulation of the interaction between the mechanically coupled volume elements at both of hot and cold sides in thermally loaded components.

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Table 1
Chemical composition of the 304L type steel in wt%.

C	Mn	Si	Cr	Ni	Mo	S	P	Cu	N	Fe
0.029	1.86	0.37	18.0	10.0	0.04	0.004	0.029	0.02	0.058	Bal

Table 2
Tensile properties of the 304L stainless steel as functions of temperature.

Temperature (°C)	*E* (GPa)	YS (MPa)	UTS (MPa)	Elongation (%)
25	192	220	557	67
150	182	162	431	53
300	179	139	403	48

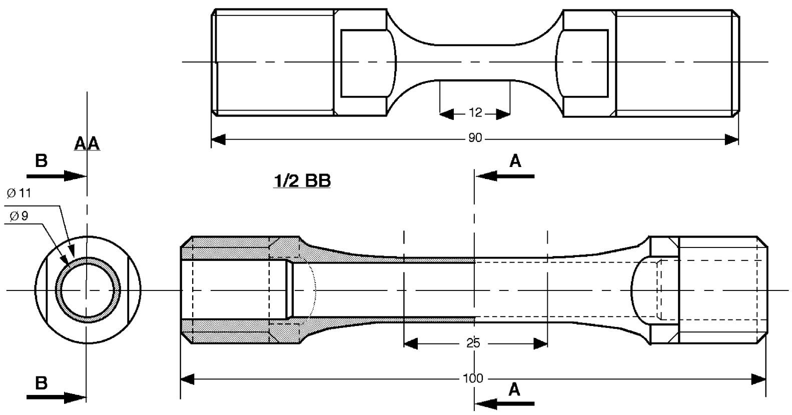

Fig. 1. Isothermal and TMF specimen geometries and dimensions.

In the majority of these studies, the authors were mostly interested in high thermal cycling ranges [2,10–12,14]. Thermal–mechanical results are often compared to isothermal fatigue tests at extreme temperatures. In our case, thermal crack network has been observed in t-junctions for high level temperature variations.

The present study is part of a wide-scale program initiated by the French Electricity Company (EDF) aiming at investigating thermal fatigue of austenitic stainless steel. The major objective of this work is to identify the effect of temperature in terms of mechanical behavior and lifetime, and to compare isothermal behavior with thermal–mechanical tests in a mid-range temperature more precisely. The present study focuses mainly on PWR conditions. As for the crack initiation behavior under thermal–mechanical fatigue, it is studied via volume element tests. The results are compared with isothermal fatigue tests at extreme thermal-cycle temperatures.

2. Experimental procedures

2.1. Material and specimen

The investigated material is a 304L type austenitic stainless steel. Its chemical composition is given in Table 1. Specimens were machined from a sheet having dimensions about $5 \times 2 \times 0.030$ m. A hyper-quenching heat treatment was performed with a temperature ranging between 1050 and 1150 °C in order to homogenize the structure and avoid chromium carbide precipitation ($Cr_{23}C_6$). The mechanical properties of the 304L stainless steel are summarized in Table 2.

As mentioned earlier, the fatigue tests under consideration are: Low Cycle Fatigue (LCF) as well as Thermal–Mechanical Fatigue (TMF) tests. Isothermal Fatigue (IF) tests were carried out on cylindrical specimens (6 mm diameter and 12 mm gauge length) (Fig. 1(a)). After machining, the surface of the specimen was mechanically polished until a granulometry of 3 μm. TMF tests were carried on tubular specimens (1 mm thickness and 25 mm gauge length) (Fig. 1(b)). A similar polishing procedure has been implemented for the specimen's exterior surface.

2.2. Apparatus

IF tests were carried out via a triangular strain signal under a strain ratio $R_\varepsilon = -1$ and a frequency of one second per cycle (1 Hz). Both hydraulic and electromechanical machines were used in this study with a longitudinal extensometer used to record the total strain.

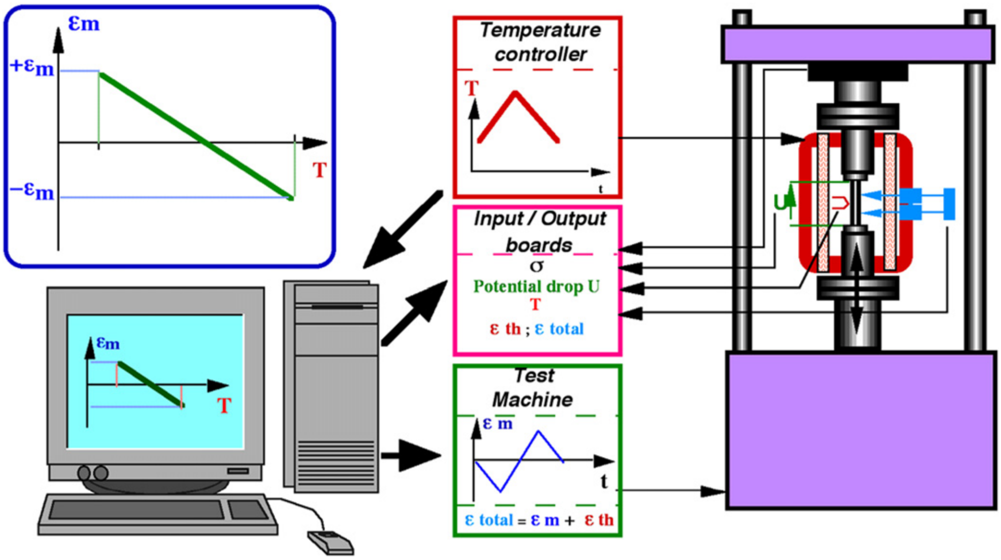

Fig. 2. Thermal–Mechanical Fatigue (TMF) facility.

Moreover, TMF tests were conducted using servo-hydraulic and electro-mechanical machines. A computer generates two synchronous signals of temperature and mechanical strain. It records stress, total strain and variation of damage signals (Fig. 2) [15].

In the present paper, for Out-of-Phase (OP) thermal–mechanical test, the temperature range is derived from thermal–hydraulic computations conducted at EDF. These calculations take into account fluctuations for the piped water temperature. During IP and OP tests, specimens were thermally cycled between 90 and 165 °C under a strain ratio $R_\varepsilon = -1$ and a period of 30 seconds per cycle. Cooling and heating rates are both equal to 5 °C per second.

The specimen damage is detected by means of an electrical procedure: the test is stopped when the potential difference exceeds 12.5%. In our case, this criterion corresponds to 6 mm crack propagation on the surface. It is important to note that N_f stands for the number of cycles required to obtain such a crack.

Cyclic hardening tests were applied on element of volume specimen in TMF tests (tubular specimen) for different strain amplitude. A single period of 30 seconds per cycle (0.033 Hz) was used throughout the different levels of mechanical strain per specimen. Two cycles of mechanical strain and temperature were tested: OP and IP cycles.

3. Results and discussions

3.1. Stress response to cyclic loading

3.1.1. Isothermal loading

The stress–strain hysteresis loops obtained at half lifetime (Fig. 3) indicate the cyclic behavior at two different temperature levels, 90 and 165 °C respectively. It is pertinent to note that hysteresis loops observed at 90 °C are dissymmetric compared to those observed at 165 °C at the same mechanical strain range. At 165 °C, the inelastic character of the studied material is more pronounced than at 90 °C with more widely opened loops. This difference of behavior is very interesting. In fact, even for such a small temperature variation (from 90 to 165 °C), an often neglected question arises, mainly that of the effect of such variation on the mechanical behavior for anisothermal loading. Most frequently, the problem is simplified by choosing an equivalent appropriate temperature to predict the response of a complex structure subject to anisothermal loading.

3.1.2. Thermal–mechanical loading

Fig. 4 illustrates a comparison between the hysteresis loops at the 20th cycles of IP and OP tests at the same mechanical strain range (0.16%). The results are reviewed in a cyclic hardening curve (Fig. 5), while the parameters of the hardening law (Eq. (1)) are summarized in Table 3.

$$\Delta\varepsilon_m/2\ (\%) = \left[(\Delta\sigma/2)/A_1\right] + \left[(\Delta\sigma/2)/A_2\right]^{1/n} \qquad (1)$$

According to these achieved results, we can deduce the following notes:

- The 304L austenitic stainless steel is harder during an Out-of-Phase cycle, than during an In-Phase cycle. Similar results have been achieved in a previous study [16] in the case of thermal–mechanical fatigue tests performed on 316L stainless

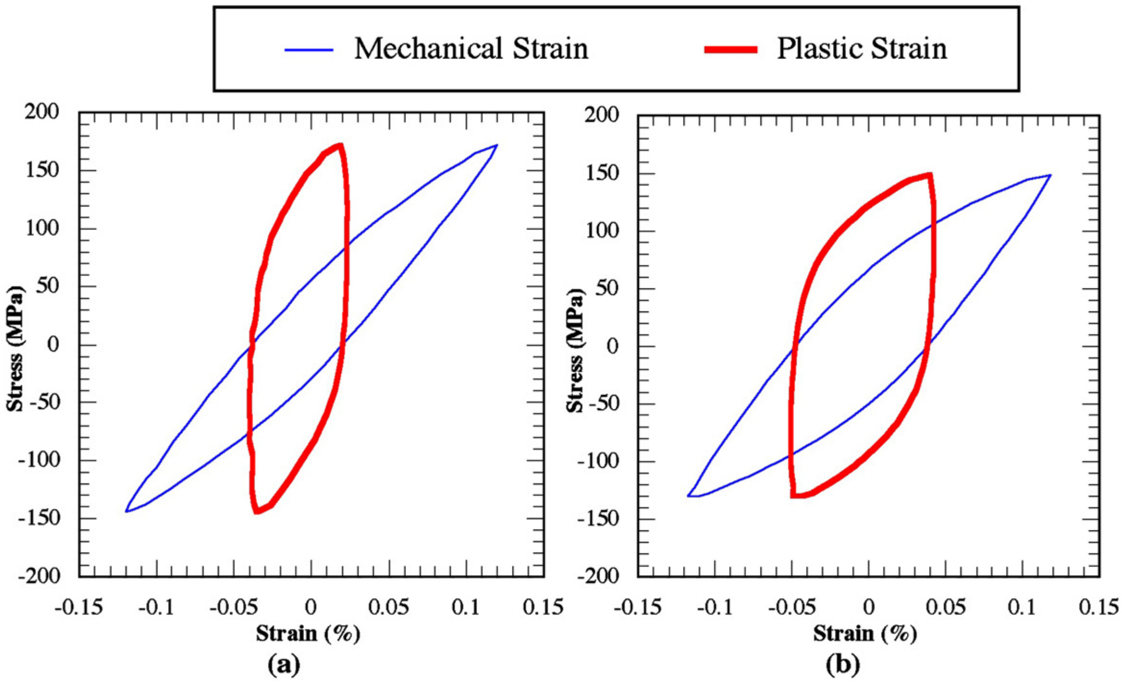

Fig. 3. Stress–strain loops at half lifetime in isothermal fatigue tests, $f = 1$ Hz, $\varepsilon_m = \pm 0.12\%$: (a) $T = 90\,^\circ\mathrm{C}$, (b) $T = 165\,^\circ\mathrm{C}$.

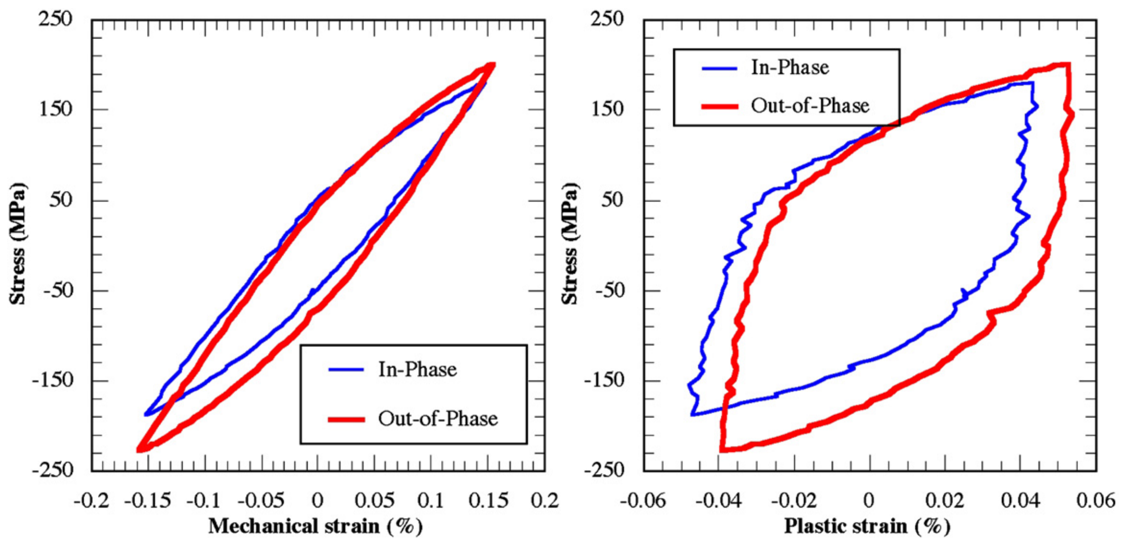

Fig. 4. Stress–strain loops for In-Phase and Out-of-Phase thermal–mechanical fatigue tests, $\varepsilon_m = \pm 0.16\%$.

steel at temperature ranges varying between 250 and 500 °C. As for Zhang et al. [17], they highlighted that the influence of the thermal–mechanical cycle is significant according to the applied stress–strain loops in the case of steel tools.

- With in phase cycle, plasticity occurs at lower stress level (120 MPa) comparing to the Out-of-Phase TMF tests (160 MPa).

At half lifetime, stress–mechanical strain loops are presented (Fig. 6) in the case of an Out-of-Phase test. As can be noticed, the material has a slight important inelastic character at low mechanical strain amplitudes ($\varepsilon_m = \pm 0.18\%$). It is important to note that the same behavior has been identified in the case of IP tests.

At half time, the comparison between IP and OP loops (Fig. 6) has suggested that the softening process is slightly important in the case of Out of Phase test.

Table 3
Coefficient of the cyclic hardening curve in thermal–mechanical fatigue tests ($N = 20$ cycles).

Type of test	A_1	A_2	n'
Out-of-Phase	1932.7	343.5	0.161
In-Phase	1932.7	300.8	0.176

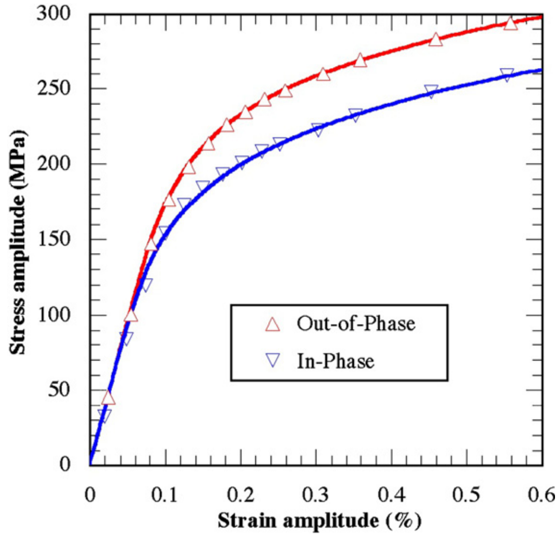

Fig. 5. Cyclic hardening curves according to mechanical strain of TMF tests (PO and IP), 90/165 °C, $f = 0.033$ Hz, $R_\varepsilon = -1$.

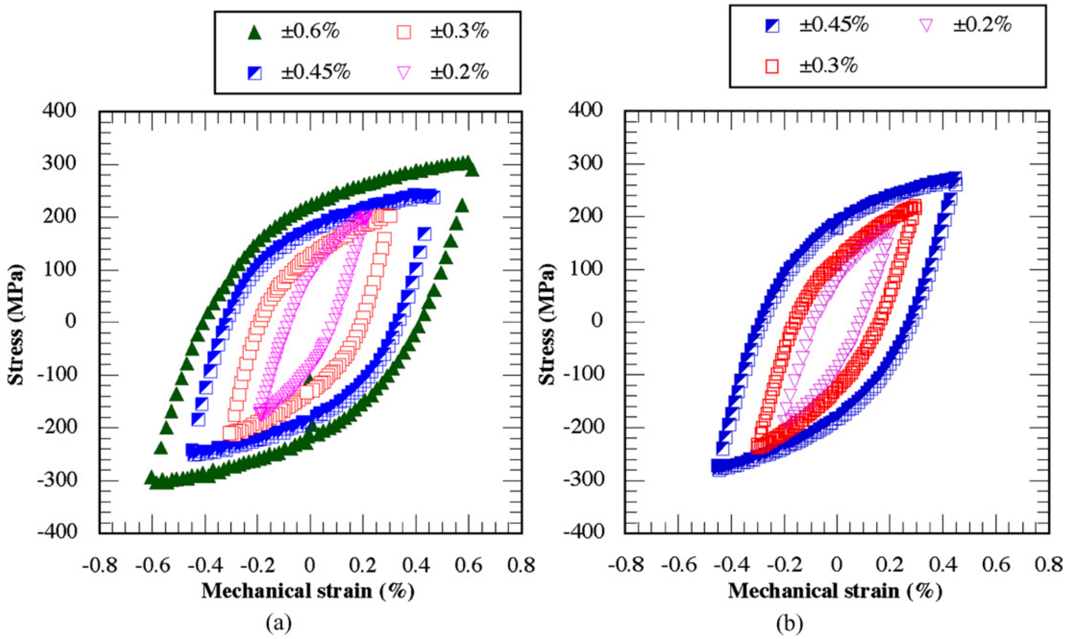

Fig. 6. Stress–strain loops at half lifetime for (a) Out-of-Phase and (b) In-Phase thermal–mechanical fatigue tests.

3.2. Cyclic stress–strain behavior

Fig. 7 shows the evolution of maximal and minimal stress (σ_{max} and σ_{min}) for isothermal tests at 90, 165 and 320 °C. We can note that for each temperature, absolute values of σ_{max} and σ_{min} rise in the first 10 cycles (hardening), then they decrease (softening) until rupture.

It is important to note that the evolution is more important at 90 °C than at 320 °C.

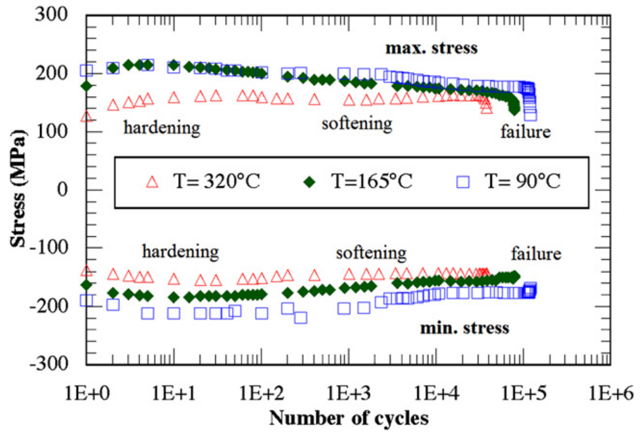

Fig. 7. Comparison of cyclic hardening/softening curves for isothermal fatigue tests, $f = 1$ Hz, $\varepsilon_m = \pm 0.2\%$.

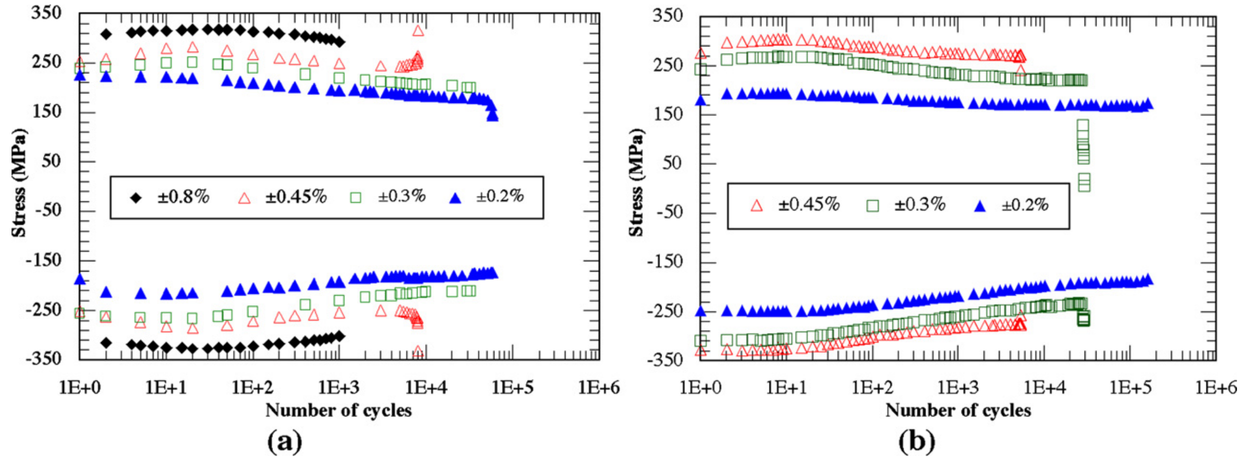

Fig. 8. Cyclic hardening/softening curves of several TMF tests ($f = 0.033$ Hz, $T_{min} = 90\,°C$, $T_{max} = 165\,°C$): (a) Out-of-Phase tests, (b) In-Phase tests.

This kind of behavior was identified in the majority of studies that deals with the austenitic stainless steels [14,16] and tempered martensitic steels [18].

The comparison between IP and OP tests performed with ±0.2% is presented in Fig. 8. It shows that the stress level is higher in the first cycles in the case of OP test. A more important softening is also observed for OP tests.

We can note also that in the case of IP solicitation, the σ_{max} level decreases lightly during cycled loading. Moreover, an initial compression mean stress is also identified during the In-Phase tests as compared to the Out-of-Phase tests [3,11,14].

3.3. Lifetime behavior

The lifetime–stress curve is plotted for the isothermal fatigue tests at 90 and 165 °C (Fig. 9). In high-level loading, the temperature test presents no effect. However, a significant decrease of lifetime is observed when the temperature rises from 90 to 165 °C at low stress amplitudes. Here, it's important to note that similar results have been reported in previous work given in literature at IF tests [5,7,19].

As shown in Fig. 10, thermal–mechanical fatigue lifetime of the 304L steel is compared to those of isothermal fatigue tests. In our case, the thermal–mechanical lifetime (via OP tests) appears equal to match the isothermal fatigue endurance at 165 °C.

In-Phase TMF tests showed a lifetime longer than the Out-of-Phase TMF tests [18,20]. As can be observed, the In-Phase tests turn out to be comparable with isothermal fatigue tests at minimum temperature.

It is also important to note that the thermal–mechanical cycle plays a crucial role in fatigue lifetime. This function is probably more significant for high lifetimes, where the difference between isothermal tests at 90 and 165 °C turns out to be important (Fig. 9). However, due to the very high expenses of thermal–mechanical tests relative to high lifetime, experiment area's endurance diagram pertaining to the considered material could not unfortunately be treated.

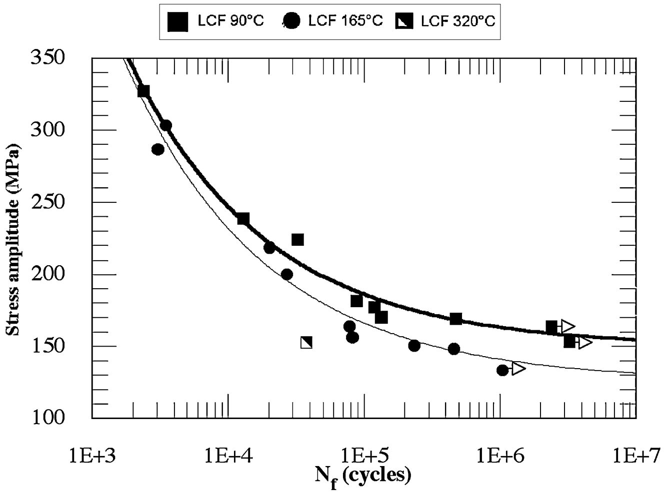

Fig. 9. Stress–lifetime curve for isothermal fatigue tests.

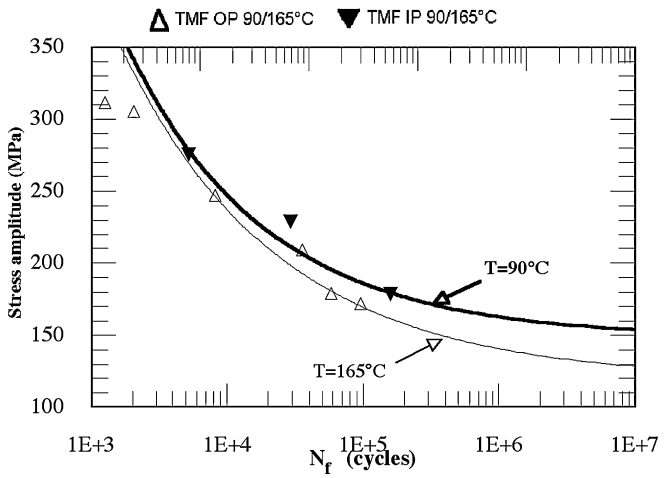

Fig. 10. Comparison of lifetime curves for thermal–mechanical fatigue tests and isothermal fatigue tests.

3.4. Damage of the 304L stainless steel

3.4.1. Isothermal tests

The tests carried out at 90, 165 and 320 °C led to the initiation and the propagation of a dominant crack perpendicularly to the direction of loading. In all cases, the crack path has remained transgranular. It is important to note that the presence of a relief associated with bands intrusions extrusions and/or bands of deformation is interesting (Fig. 11).

The comparison of the cracks at 90 and 320 °C for the same strain amplitude (Fig. 12) suggests that at higher temperature degrees, the damage of material starts by the formation of twist bands which are much denser than at low temperature ($T = 90\,^\circ\mathrm{C}$). In fact, at 90 °C, the crack lips present fewer deformation bands. At 320 °C, the material presents less viscoplastic character, and the deformation is accompanied by the creation of persistent bands which reveal a clear manifestation of fatigue and crack initiation (Fig. 11). Once initiated, the cracks follow the direction of the intrusion and extrusion bands [5].

3.4.2. Thermal–mechanical tests

In both In-Phase and Out-of-Phase tests, transgranular cracks have been observed, showing a typical fatigue that is apparent at stage I (the crack initiation and propagation under an angular aperture of approximately 45° with the stress axis), as well as at stage II (propagation under 90° with the stress axis) (Fig. 13) [6].

The fracture surface of a thermal–mechanical fatigue crack (Fig. 14) is characterized by fatigue striation perpendicular to the direction of propagation. This type of observation is difficult to detect for small strain amplitudes. The same type of surface crack can be noted via isothermal fatigue tests.

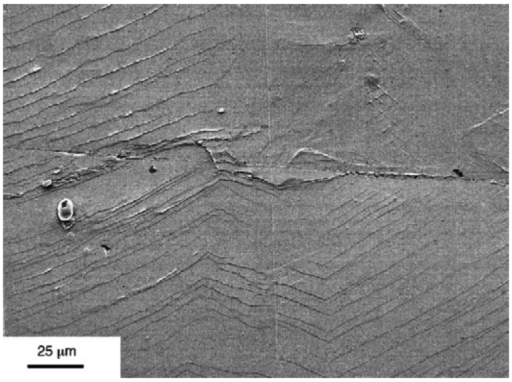

Fig. 11. Fatigue crack initiation from bands of deformation, $T = 320\,^{\circ}\mathrm{C}$, $\varepsilon_m = \pm 0.2\%$, $f = 1$ Hz.

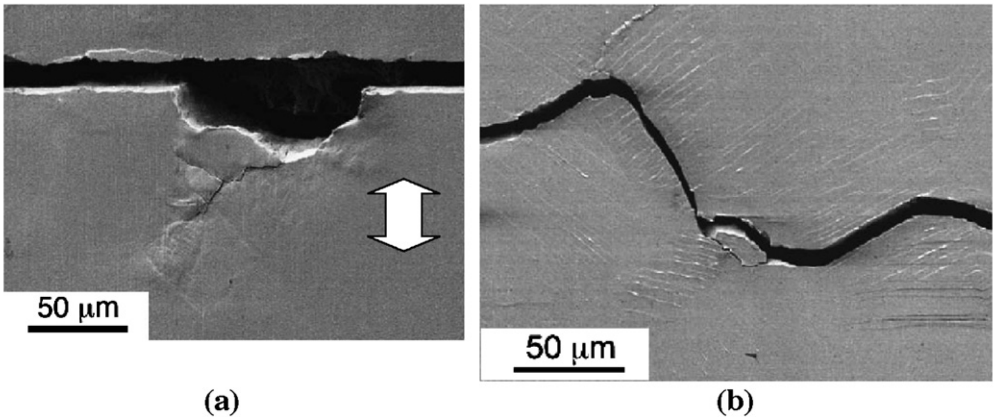

Fig. 12. Bands of deformation to the lips of fatigue cracks, $f = 1$ Hz, $\varepsilon_m = \pm 0.2\%$: (a) $T = 90\,^{\circ}\mathrm{C}$, (b) $T = 320\,^{\circ}\mathrm{C}$.

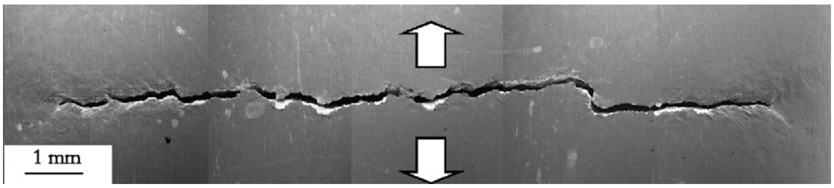

Fig. 13. Thermal–mechanical fatigue crack: In-Phase test, $\varepsilon_m = \pm 0.2\%$, $T_{\min} = 90\,^{\circ}\mathrm{C}$, $T_{\max} = 165\,^{\circ}\mathrm{C}$, $f = 0.033$ Hz.

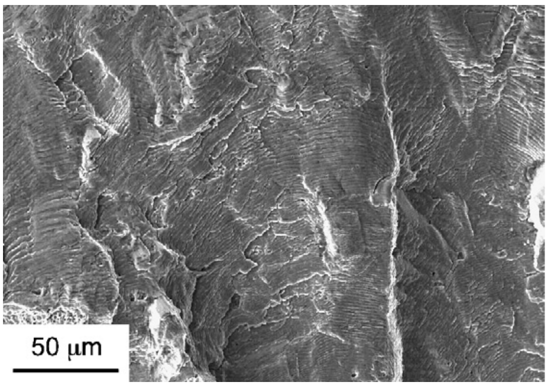

Fig. 14. Thermal–mechanical fatigue striations: Out-of-Phase test, $\varepsilon_m = \pm 0.3\%$, $T_{\min} = 90\,^{\circ}\mathrm{C}$, $T_{\max} = 165\,^{\circ}\mathrm{C}$, $f = 0.033$ Hz.

4. Conclusions

The present investigations of thermal–mechanical fatigue of austenitic stainless steel at middle range temperatures have provided the following conclusions:

- At both temperatures, 90 and 165 °C, the alloy's cyclic response is characterized by an initial hardening followed by a cyclic softening. A similar behavior is witnessed at 320 °C.
- No temperature effect on lifetime for the high strain range has been observed. However, lifetime appears to decrease when the temperature increases for a number of cycles higher than 10^5.
- An inconsistency difference in behavior pertaining cyclic hardening tests has been identified between the In-Phase thermal–mechanical fatigue tests and the Out-of-Phase tests between 90 and 165 °C.
- Thermal–mechanical damage seems to be similar to isothermal damage concerning the shorter lifetimes. In-Phase thermal–mechanical test increases lifetime with respect to the Out-of-Phase test.
- In all undergone tests, whether isothermal fatigue test or thermal–mechanical fatigue one, the damage of the 304L is characterized by the initiation and the propagation of a transgranular principal crack perpendicular to the load direction.

The temperature range studied was determined by the cooling operating conditions. It would be interesting to investigate the lifetime of the studied material at 320 °C and the effect of thermal–mechanical loading (90/165 °C) at low strain amplitude.

Indeed, many results have shown that for large life, the endurance of the material is affected by temperature (between 90 and 165 °C).

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