Thermal response of metastable stainless steel 304L under cyclic loading at room and low temperatures

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Abstract:

In this study, a special attention is paid to explain the material's thermal response during cyclic loading (i.e. self-heating tests) at different initial states for the metastable austenitic steel 304L. More precisely, the effect of a pre-hardening by applying a tensile plastic pre-strain is studied at room and low temperatures. In addition, microstructural evolution after cyclic loading is investigated using FERITSCOPE, scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The obtained results from samples without pre-strain (PS) show that by decreasing the test temperature, the mechanical properties of the material are changed; for instance, the yield stress increases and the sample needs more stress amplitude for getting the same value of the stabilized mean temperature. Therefore, the self-heating curves shift to the right side (i.e., higher stress levels). It means that the fatigue limit of this material is improved by decreasing the test temperature. On the other hand, the results of self-heating tests on pre-strained samples have enabled us to investigate the effect of an initial volume fraction of martensite on the cyclic behavior of this material. As for temperature, the self-heating curves shift to the right side showing the improvement of the fatigue limit by increasing the pre-strain ratio.

Keywords: metastable stainless steel / fatigue / martensitic transformation / self-heating

1 Introduction

Austenitic stainless steel materials have found a wide range of applications due to interesting properties such as high ductility, good corrosion resistance, low cost, easy for machining and plenty availability. In metastable austenitic stainless steels, the γ-austenite (FCC) can transform into the α'-martensite (BCC) and/or to ε-martensite (HCP) under the deformation-induced transformation [1], [2]. Therefore, the mechanical properties of these materials are significantly affected by this deformation-induced martensitic transformation. The martensitic transformation can occur upon monotonous mechanical loading as well as cyclic loading by imposing considerable magnitude of strain amplitudes (i.e., low cycle fatigue). However, enough knowledge about the effect of martensitic transformation on high cycle fatigue (HCF) of metastable stainless steel is still missing in the literature. Consequently, further efforts are needed in order to determine the nature of this phenomena and its effect on high cycle fatigue properties of this material.

The traditional methods for fatigue characterization are extremely time consuming and costly. Hence, several alternative methods have been developed to perform a rapid evaluation of fatigue properties.

Since cyclic loading is an energy-dissipating mechanism, it is accompanied by temperature rising of the material that undergoes a fatigue test. Therefore, alternative fatigue characterization methods are mostly based on the assessment of the material temperature variations occurred upon fatigue loading, which is generally so-called self-heating method. The self-heating method is based on measuring of the temperature rising at the surface of the specimen as result of the microplasticity phenomenon. Anyway, the self-heating method allows a rapid determination of the high cycle fatigue limit, but the prediction of the fatigue curve should be considered for such special materials like metastable stainless steels. Moreover, the self-heating measurements can help to better understand the mechanisms of simultaneous micro-plasticity and martensitic transformation during cyclic loading.

This study is focused on the self-heating response of the metastable austenitic steel 304L. More precisely, this work aims at understanding the fatigue behavior of this material via self-heating method. Benefiting from this robust and fast method, effects of different parameters on fatigue properties can be efficiently studied. The results provide us to make a contribution towards determining the relation between the results obtained from self-heating tests and those obtained from classical fatigue ones.

2 Test procedure

2.1 Material

Considered material in this study is metastable austenitic stainless steel 304L. The chemical composition of this material is given in Table 1.

Table 1. Chemical composition of stainless steel 304L

Chemical composition	C	Mn	P	S	Si	Cr	Ni	N	Mo	Cu	Iron
(wt %)	0.029	1.89	0.028	0.001	0.33	18.20	9.32	0.08	0.26	0.28	Balance

For preparing the specimen, before machining, in order to eliminate the internal stress and the history effects due to initial manufacturing, the cylinders with diameter of 30mm were annealed at T=1050°C for 10 minutes using argon gas and then, were quenched in water. As one can see in Figure 1, after this heat-treatment, a homogeneous and purely austenitic microstructure was obtained. The grain size of heat-treated material is about 100-150 μm.

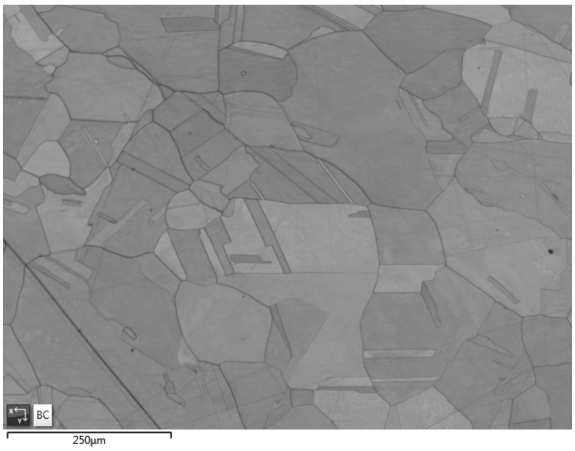


Fig. 1. Microstructure of heat-treated material

The heat-treated cylinders were machined to obtain the final shape of the specimens. Dimensions of the specimen is depicted in Figure 2.

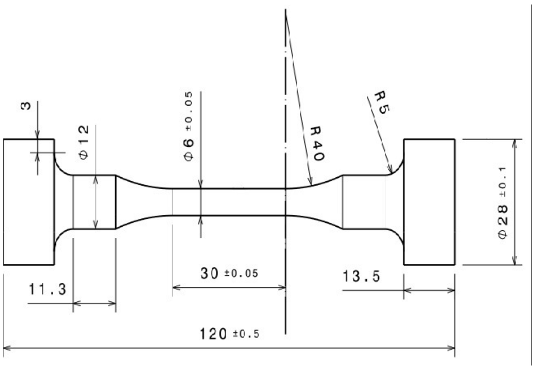


Fig. 2. Schematic and dimensions of the specimen (all dimensions are in mm)

2.2 Experimental details

Uniaxial tensile and self-heating tests were carried out using a servo-hydraulic traction-torsion machine (TTC) with a capacity of ±100kN and ±1000N.m. The deformation was measured by an Epsilon axial extensometer with L_0 of 25 mm. Three K-type thermocouples were used for measuring the temperatures of the sample, the lower and upper jaws.

For realizing the tests at different temperatures by using the chamber, special jaws were designed. The shape of sample and designed jaws enabled us to apply different loading ratios. Servathin chamber was used for performing the tests at low temperatures up to -50°C and another specified cooling chamber using liquid nitrogen was applied for lower temperatures such as -90°C. This experimental setup is shown in Figure 3.

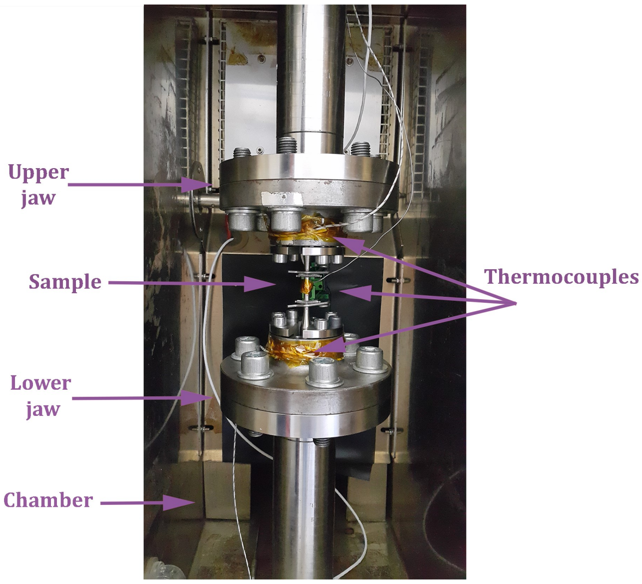


Fig. 3. Experimental setup for realizing the test at low temperatures

A uniaxial tensile test was conducted at room temperature, until rupture, under strain control mode according to the standard DIN EN ISO 6892-1 with strain rate of 0.00025 s^{-1}. The mechanical properties of the studied material are demonstrated in Table 2.

Table 2. Principal mechanical properties of stainless steel 304L

Material	Yield stress (MPa)	Young's modulus (GPa)	Tensile strength (MPa)	Percentage elongation after fracture (%)
304L	272.3	176	617.2	78.39

2.3 Self-heating procedure

A self-heating test consists of a series of cyclic loading with increasing stress amplitude. At each stress amplitude for the same specimen, the cyclic loading is carried out with the same frequency and number of cycles. The mean temperature changes (θ), which is given by equation (1), is registered during the test. The temperature elevation reaches a stabilized value after a specific time (Fig. 4). This stabilized mean steady state temperature ($\overline{\theta}$) is determined for each loading block and is plotted versus stress amplitude which is so-called self-heating curve [3], [4].

$$\theta = T_{Specimen} - 0.5 \times (T_{upper\ jaw} + T_{lower\ jaw}) \qquad (1)$$

In this study, the considered testing frequency (f) and the loading ratio (R) are 10 Hz and -1, respectively. For each testing block, 6000 cycles were carried out. At the end of each loading block, the temperature decreases until attaining the initial equilibrium state of the sample (i.e., T=T0). This process was applied for different stress amplitudes and was stopped when the temperature change did not achieve a stabilized value until 6000 cycles.

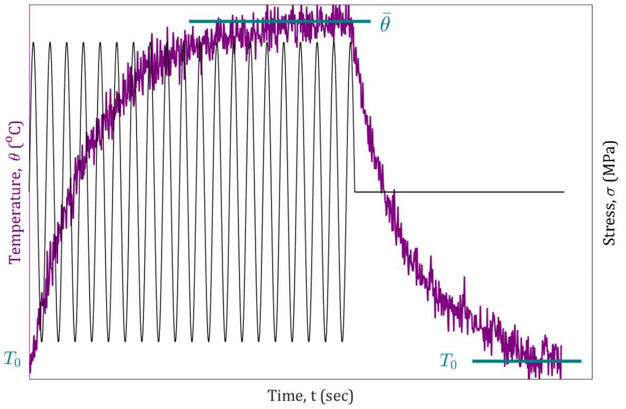
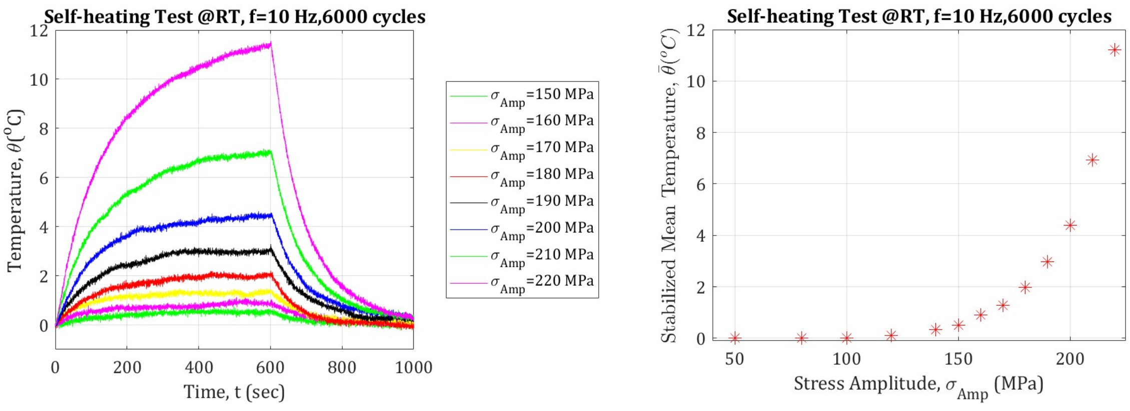


Fig. 4. Evolutions of temperature and stress versus time during one loading block

3 Results

3.1 Effect of temperature

The temperature evolution during loading blocks, with different stress amplitudes for the studied material at room temperature (RT) is indicated in Figure 5a. This figure shows that the temperature increases rapidly at the beginning of the test (about 2000 cycles) and then it tends to a stationary value. This stabilization corresponds to a constant dissipated heat source (i.e. a thermodynamic equilibrium between the dissipated energy and induced one by mechanical loading). The higher stress amplitudes lead to the higher mean steady state temperature with the same trend until it reaches to about 11°C for the stress amplitude of 220 MPa (Fig. 5b). At higher stress amplitudes, the evolution of temperature did not stabilize and it reached around 44°C after 6000 cycles and in contrast, for stress amplitude lower than 150 MPa, this value remained lower than 0.4°C.

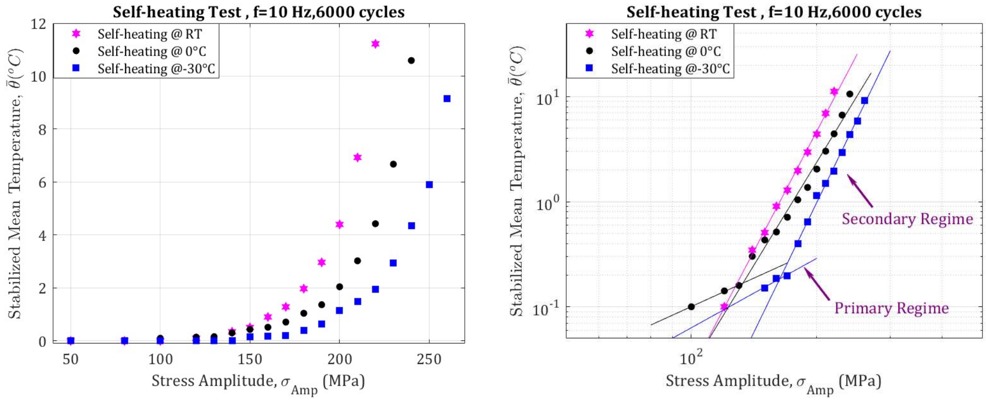


(a) (b)

Fig. 5. (a) Mean temperature evolution during different cyclic loading blocks and (b) resulting self-heating curve

Figures 6a and 6b show the results of self-heating curves at different temperatures on linear and logarithmic scales diagrams, respectively. By decreasing the test temperature from room temperature to - 30°C, the mechanical properties of the material seems to be improved. The yield stress of the material increases from 272 MPa to 339 MPa. This effect results in shifting of the self-heating curves to the right side. Such result indicates the improvement of the fatigue limit of the material. The maximum volume fraction of the martensite measured by FERITSCOPE after self-heating tests is lower than 0.5%. Therefore, one can consider that this evolution of fatigue limit is due to temperature effect on the mechanical properties of the material but there is no notable influence relevant to martensitic transformation on these self-heating curves.

The results plotted on the logarithmic scale (Fig. 6b) indicate that at room temperature there is only one self-heating regime while by decreasing the test temperature, two regimes can be observed. This results in the variation of the curves slopes between the primary and the secondary regimes.



(a) (b)

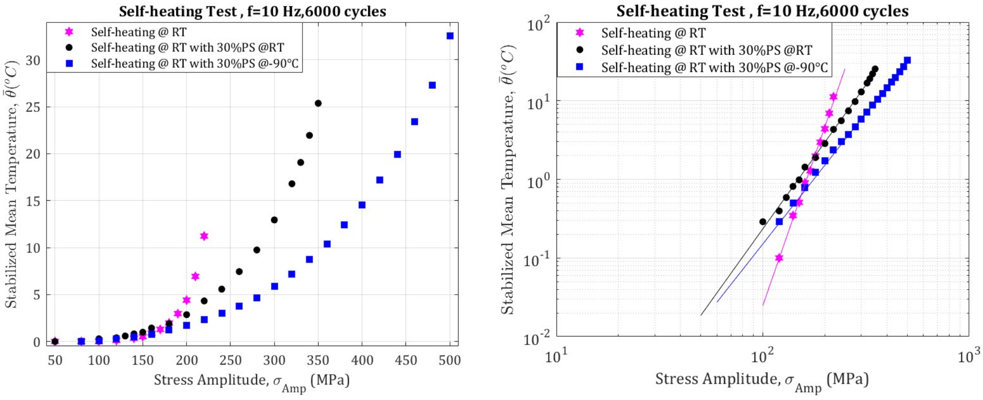
Fig. 6. Self-heating curves at different temperatures (a) linear scale (b) logarithmic scale

3.2 Effect of a plastic pre-strain and the initial volume fraction of martensite

In this section, the effect of a plastic pre-strain is studied by performing self-heating tests at room temperature on pre-hardened samples at different temperatures. These samples were pre-deformed up to 30% strain at RT and low (i.e. – 90°C) temperature. After pre-strain at RT and – 90°C, the volume fraction of martensite (VFM) was measured using a FERITSCOPE FMP30. After 30% pre-strain at RT, almost no martensite volume fraction has occurred and after 30% pre-strain at – 90°C, VFM was quantified around 33%. For easy understanding, we simply use "RT30" and "LT30", in the following, to stand for 30% pre-strained specimens at RT and – 90°C, respectively. These two different initial states (i.e., RT30 and LT30) provide us to examine simultaneously the influence of initial VFM and the effect of a plastic pre-strain on the self-heating behavior of the material.

Figures 7a and 7b show the results of self-heating tests realized at room temperature on RT30, LT30 and virgin (i.e., the specimen without pre-strain) specimens. By comparing the self-heating curves obtained from virgin and RT30 specimens, one can note that the self-heating curve shifts to the right side. It means that the pre-strain at RT improves the fatigue limit of the material which is in line with the results presented by S. Gupta et al. [5]. The authors mentioned that for every 20% increment in pre-straining, the fatigue life increases by 40 to 80 MPa.

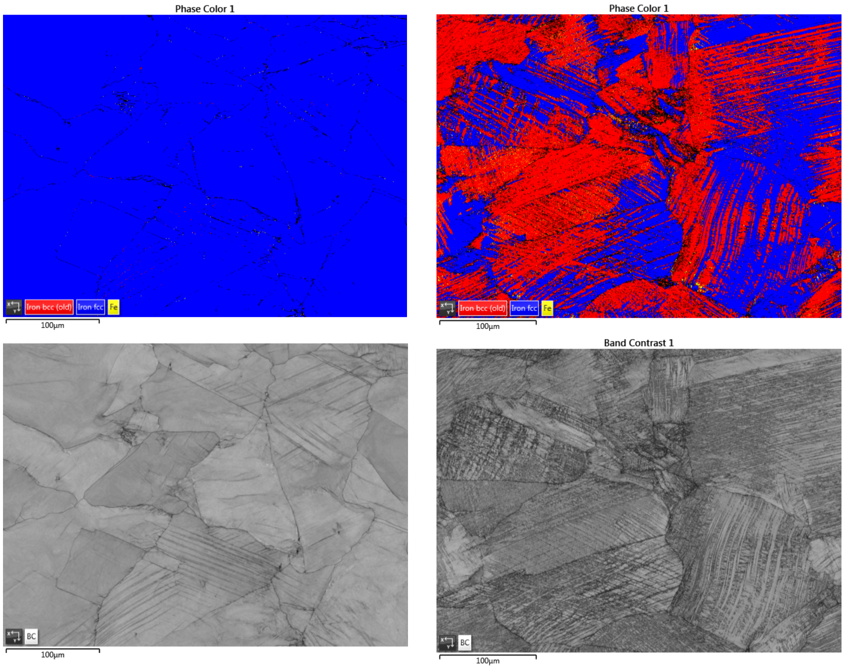
By comparing the self-heating curves obtained from RT30 and LT30 specimens, once again, self-heating curve shifts to the right side. When the material was deformed up to the same plastic strain, lower temperature leads to higher amounts of VFM. This phase transformation results in appearance of a secondary hardening on the tensile tests curves causing the improvement of the mechanical properties and the fatigue limit of the material. Consequently, self-heating curves obtained on RT30 and LT30 specimens confirm the considerable influence of martensitic transformation. This result is in accordance with the finding of M. Smaga et al. [6] who indicated that one of the advantages of martensitic transformation is increasing the lifetime in the HCF regime. It is worth noting that there is one self-heating regime observed on pre-strained samples (Fig. 7b).



(a) (b)

Fig. 7. Self-heating curves at RT for the virgin, RT30 and LT30 specimens (a) linear scale (b) logarithmic scale

In Figures 8a and 8b, we can see EBSD observations of deformed samples after self-heating tests at room temperature. α'- martensite (BCC structure), ε-martensite (HCP structure) and austenite (FCC structure) phases are represented by red, yellow and blue colors, respectively. The formed martensite is in the shape of needles embedded in the austenite grains. These figures indicate that the extent of the martensite is a function of temperature and plastic strain. The VFM after self-heating tests are 0.06% for RT30 (Fig. 8a) and 40.16% for LT30 specimens (Fig. 8b). The obtained VFM at room temperature after 30% pre-strain is in accordance with the observations made by A.K. De et al. [7]. The authors stated that the deformation at room-temperature does not initiate any measurable transformation even up to 30% strain. As is seen in Figure 8b, the martensite phase forms at the inner of twins and close to the grain boundaries.



(a) (b)

Fig. 8. EBSD characterization after self-heating test at RT for (a) RT30 and (b) LT30 specimens

For the same level of plastic pre-strain, the strain-induced martensite formation increases by decreasing the test temperature. It means that there is a direct relation between the test temperature and martensite formation.

4 Conclusion

The effect of temperature and pre-strain was studied on the self-heating curve of austenitic stainless steel 304L. The obtained results confirmed that the fatigue properties could be improved by decreasing the test temperature or by applying a plastic pre-strain.

The EBSD observations after self-heating tests indicate that higher volume fraction of α'-martensite appears for pre-strained sample at low temperature. The VFM was measured by FERITSCOPE after performing pre-strain as well as after self-heating test. It is worth mentioning that the measured values did not considerably change after self-heating test. In addition, the obtained values using FERITSCOPE approximately complies with those acquired by EBSD measurements.

This study enables us to make a contribution towards determining the relation between the results obtained from self-heating tests and those obtained from classical fatigue ones.

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