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Effect of Temperature and Strain Rate on Material Characteristics of Al319-T7

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Abstract

An extensive experimental investigation of different temperatures and strain rates has been carried out on aluminum alloy Al319-T7. It is found that elevated temperature tends to decrease the strength in tensile and cyclic tests, whereas increasing strain rate appears to improve the strength, and in strain-controlled isothermal fatigue tests, higher temperature results in shorter fatigue life for a given stress amplitude. In addition, increased strain rates are found to improve the fatigue life in high-temperature tests, while their effect is negligible in room-temperature tests. In-phase (IP) and out-of-phase (OP) thermo-mechanical fatigue (TMF) tests with and without dwell time are also conducted in this paper. The results reveal that for the same applied total strain amplitude, OP tests, owing to their larger mechanical strain amplitude, are more critical than IP tests. Furthermore, stress relaxation happening in dwell time will help to increase the fatigue life, compared to those tests without dwell time.

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Keywords: thermomechanical fatigue; cast aluminum alloy; high temperatre; cyclic behavior; stress-strain response

1. Introduction

Nowadays, aluminum alloys are used more frequently to replace cast iron and steels in various mechanical and structural components of vehicles for the purpose of increasing fuel economy by reducing weight. One typical use is

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in the cylinder heads of internal combustion engines, the operating temperatures of which have been increased to improve engine efficiency. The peak temperature they may experience is up to 300˚C [1]. These components subjected to high cyclic thermal and service loads are prone to fatigue failure. Thus, proper understanding of the material behavior at high temperatures is required.

Engler-Pinto et al. [2] investigated the thermo-mechanical fatigue behavior of cast 319 aluminum alloys under high temperatures and found the stress-strain behavior is similar between in-phase and out-of-phase TMF tests. Under a given mechanical strain amplitude, fatigue life in IP tests is lower compared to OP tests. By using a two-state-variable unified inelastic constitutive model proposed by Sehitoglu [3], Engler-Pinto et al. [4] determined the constants in this model systematically from isothermal experiments and verified its ability to simulate the material response, including cyclic softening and thermal recovery, by comparing it with TMF experimental results. Su et al. [5] developed an ABAQUS subroutine to analyze the stress and strain of engine heads in a thermal cycle. By extending the viscoplastic model to a three-dimensional stress state case, they predicted the strain and fatigue life of engine components and compared them with measured results. Kang et al. [6] proposed an approach to correlate the predicted fatigue life with test life in TMF tests under variable temperature and loading amplitudes.

This paper investigates the temperature and strain rate effect on the mechanical behavior of AL319-T7 under tensile tests and cyclic tests, and the fatigue life under isothermal fatigue tests and thermo-mechanical fatigue tests. Dwell time effect is also studied in both in-phase and out-of-phase TMF tests. The results and discussion in this paper provide a fundamental understanding for the future development of a finite element analysis model of automotive engine components.

2. Experimental description

2.1. Material and Specimen preparation

The material tested in the present study is aluminum alloy Al319 with T7 heat treatment (8 hours solutionizing at 495˚C, followed by boiling water quench and 4 hours aging treatment at 260˚C). This heat treatment produces an overaged microstructure that is intended to improve dimensional stability when subjected to high temperature exposure [1]. Rectangular bars are cut from cast Al319-T7 alloy cylinder heads and then machined into the test specimens, dimensions and preparation of which are prescribed by the ASTM Standard Practice for Strain-Controlled Fatigue Testing E606 [8]. Before testing, the specimens are polished using emery sandpapers of three different grain sizes to achieve a smooth finish. The specimen dimensions are slightly different for tensile and fatigue tests, and the detailed geometries are illustrated in Figure 1.

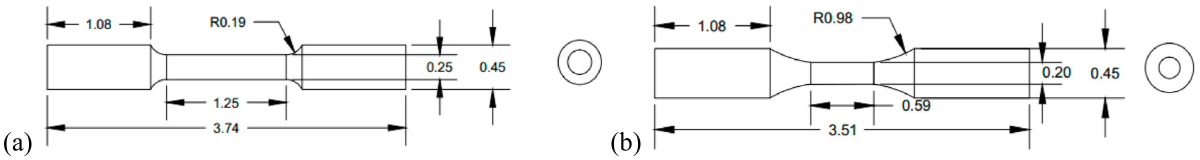


Fig. 1. Specimen dimensions for (a) tensile test and (b) fatigue test.

2.2. Experimental setup

Tensile and fatigue tests were carried out by a servo-hydraulic MTS testing machine with a 100 KN capacity load cell. The total strain was measured using an extensometer (Model No-632.54F-14) with a gage length of 12mm, which is specially prepared for high-temperature testing. Ceramic extension rods, as demonstrated in Figure 2, were mounted on the gage section of the specimen.

High-temperature tests were conducted in conjunction with an Ambrell Easyheat 10 KW heating induction coil. The temperature on the specimen was continuously monitored and controlled using a Eurotherm 2404 temperature controller. The complete experimental setup can be seen in Figure 2.

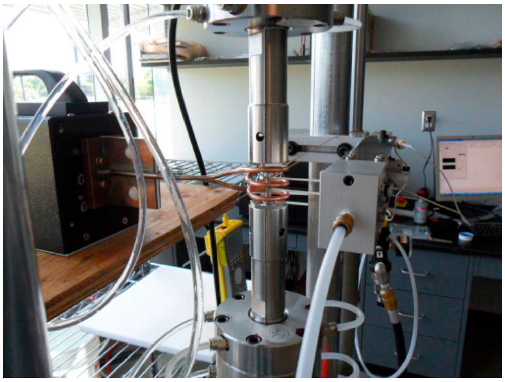


Fig. 2. Test setup with specimen, induction coil, auxiliary cooling system of the grips, and the strain gauge with ceramic extension rods.

2.3. Test procedure

All the tensile, cyclic, and isothermal fatigue tests were performed under total strain control at 5 different temperatures (25°C, 150°C, 200°C, 250°C, and 300°C), with three constant strain rates: $5x10^{-5}$ s^{-1}, $5x10^{-4}$ s^{-1}, and $5x10^{-3}$ s^{-1}.

Incremental step-stress testing was used here to determine the cyclic stress-strain behavior. As shown in Figure 3, the specimen was first cycled with an incremental strain of ± 0.05% to ± 0.5% strain amplitude, after which it was unloaded to ± 0.05% in a similar progression. This kind of loading process was repeated until the specimen fractured, and then the block at half-life was considered to be the stabilized block.

In isothermal fatigue and thermal-mechanical fatigue tests (TMF), a triangular waveform was used as the loading pattern. Two kinds of TMF cycle were considered, in-phase (IP) and out-of-phase (OP), where maximum mechanical strain occurred at maximum and minimum temperature, respectively. TMF tests with dwell time were also conducted here, in which total strain and temperature were held for 300 seconds at both tension and compression peak values; see Figure 4. The total four loading cases in this study were conducted at the strain rate of $5x10^{-5}$ s^{-1}. The thermal loading (temperature) upper limit and lower limit were 300°C and 150°C, respectively.

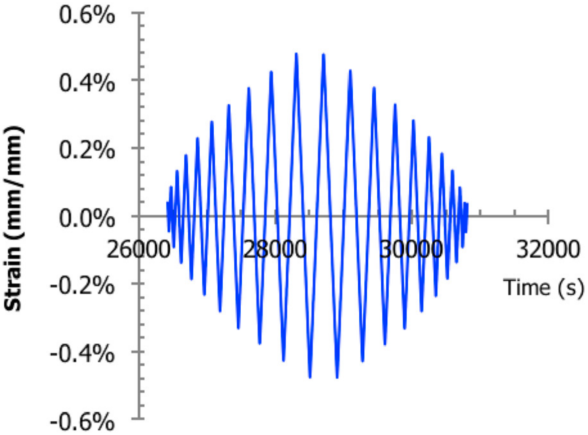
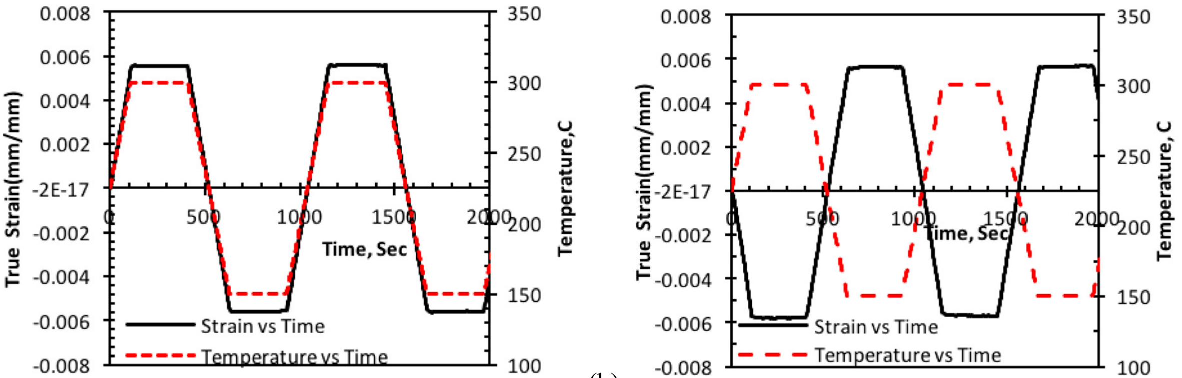


Fig. 3. Incremental strain block used for cyclic tests.



(a) (b)

Fig. 4. Loading profiles of (a) in-phase and (b) out-of-phase TMF with 300s dwell time.

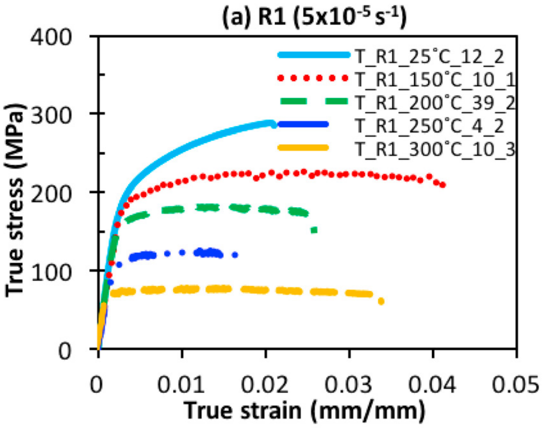
3. Results and Discussion

3.1. Monotonic tensile tests

The stress-strain curves of Al319-T7 at different temperatures with various strain rates are shown in Figure 5, from which it can be seen that the temperature has a significant effect on its monotonic tensile behavior. As the temperature increases, the yield stress and ultimate stress decrease, which reflects that the material becomes “softer” under high-temperature tensile tests.

This phenomenon is present in all strain rates and can be explained as the eutectic phase, which is fine at low temperature and becomes coarse at high temperature [7]. The sizes of the microstructural pores grow with temperature, which will also reduce the material’s strength and make it much more likely to yield.

In addition, the strain hardening behavior in room-temperature tests is more obvious than in high-temperature tests.



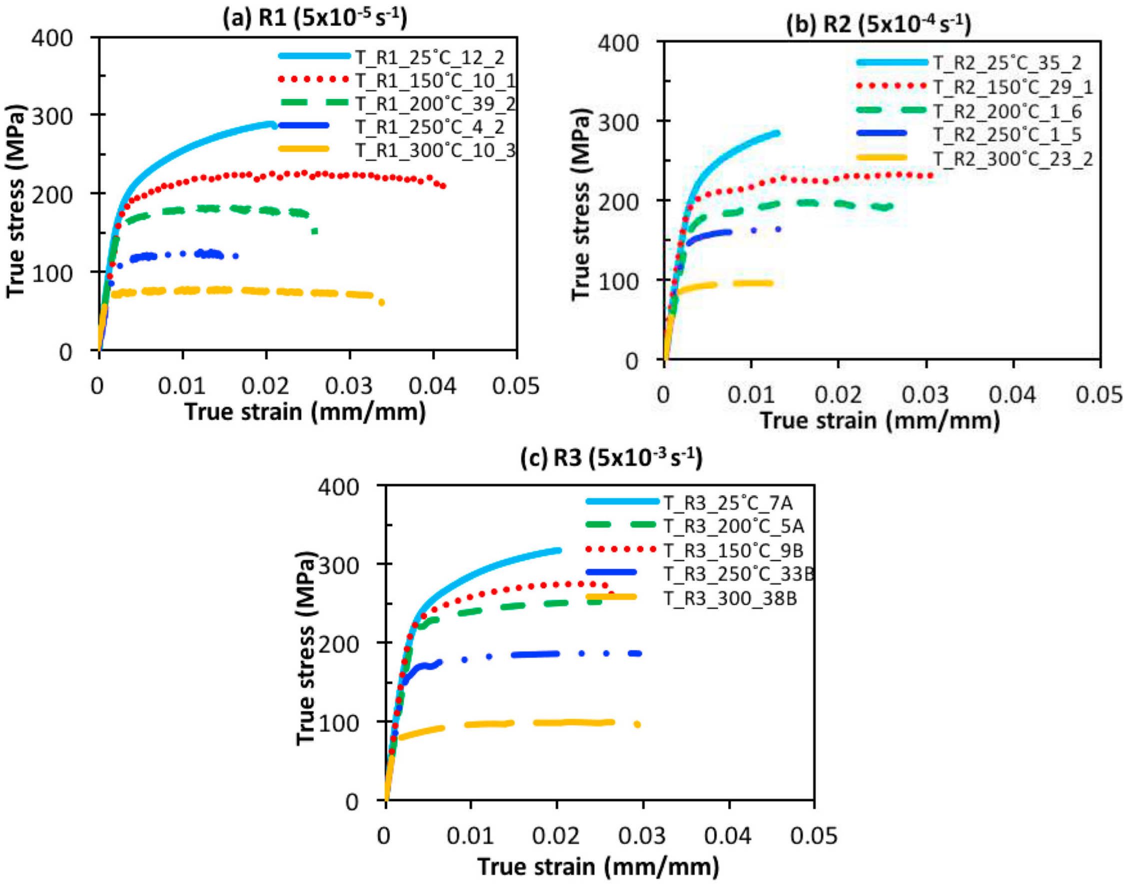
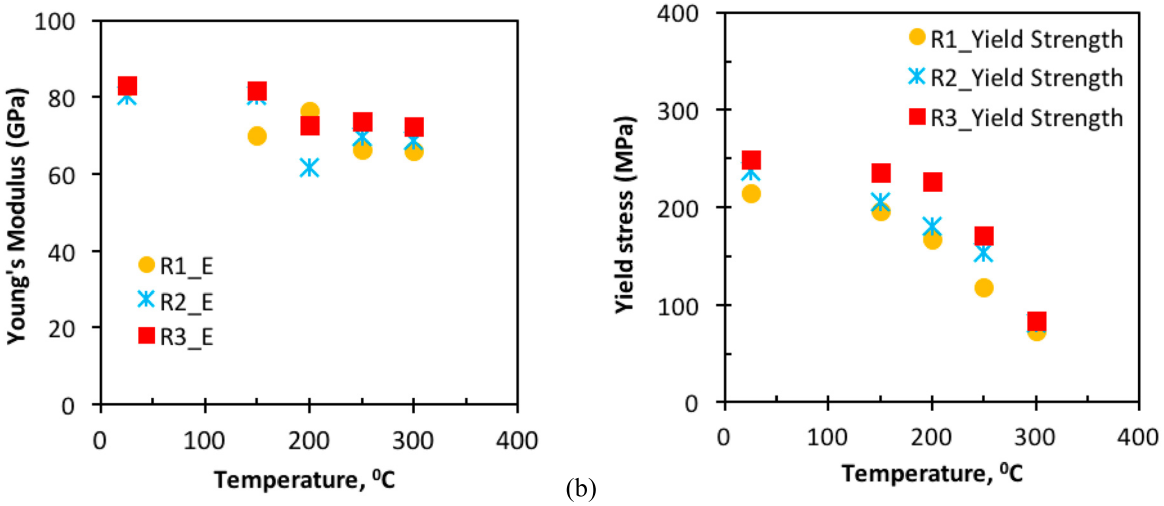


Fig. 5. Monotonic stress-strain curves at various temperatures with strain rate of (a) $5x10^{-5}$ s^{-1}, (b) $5x10^{-4}$ s^{-1} and (c) $5x10^{-3}$ s^{-1}.

Figure 6 clearly shows the trend that Young's modulus and yield stress decrease with increasing temperature. While the yield stress does not change much between room temperature and 150˚C, it reduces considerably with temperature beyond 150 ˚C. Little deviation exists in Young's modulus because the elastic part of all the tests looks almost identical and follows the linearity with nearly the same slopes.

Figure 6 also indicates that yield stress increases with strain rate at all test temperature conditions. This may be related to the lower heat diffusion time and lower heating time in the specimen with a larger strain rate. At a slower strain rate, the time of the specimen's exposure in the heat environment is longer, which will coarsen the eutectic phase and then produce a "soft" effect in the material. This can be explained as a result of thermal softening caused by the deformation energy of a material [7].

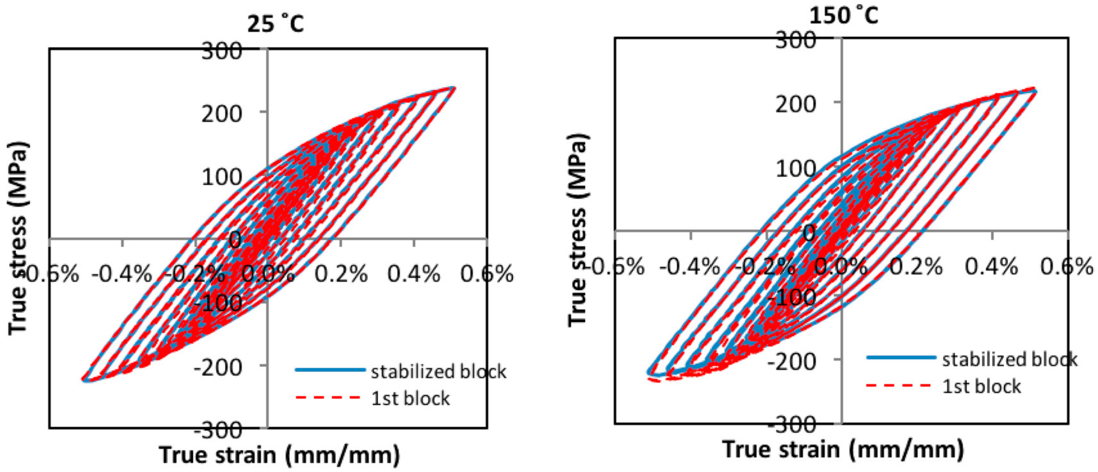


(a) (b)

Fig. 6. The changes of (a) Young’s Modulus and (b) yield stress as temperature changes.

3.2. Cyclic Behavior

Figure 7 shows the hysteresis loops of incremental tests finished at various temperatures with strain rate of 5x10^{-3} s^{-1}. The results show that, for the 5x10^{-3} s^{-1} strain rate, there is a negligible cyclic hardening/softening effect in room-temperature cyclic tests, while obvious cyclic softening behavior is found in tests at temperatures above 150˚C. Similar phenomena occur in tests with strain rates of 5x10^{-4} s^{-1} and 5x10^{-5} s^{-1}. Furthermore, with higher temperature, the cyclic softening is more noticeable.



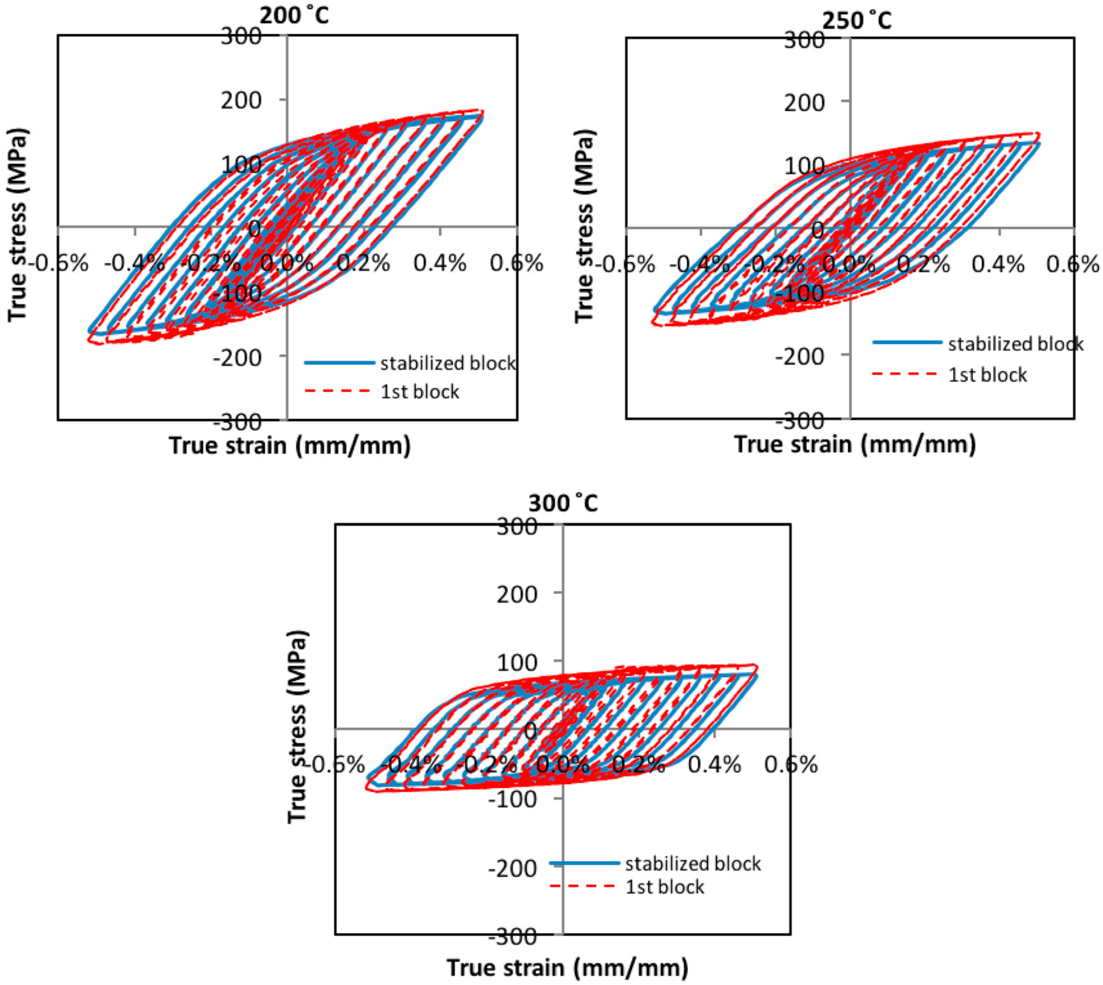


Fig. 7. Cyclic behaviors at various temperatures with strain rate of R3 ($5x10^{-3}$ s^{-1})

The influence of temperature on the cyclic behaviors of Al319-T7 is presented in Figure 8. Significant temperature dependency is observed as, regardless of the strain rate, the hysteresis loop becomes flatter as temperature increases. This means that with an increase in temperature, the hysteresis loop shows a decrease in yield strength and maximum stress under the same strain amplitude, which is also noted in monotonic tensile tests. The coarsening of the Al-Si phase in microstructure at elevated temperature accounts for this phenomenon.

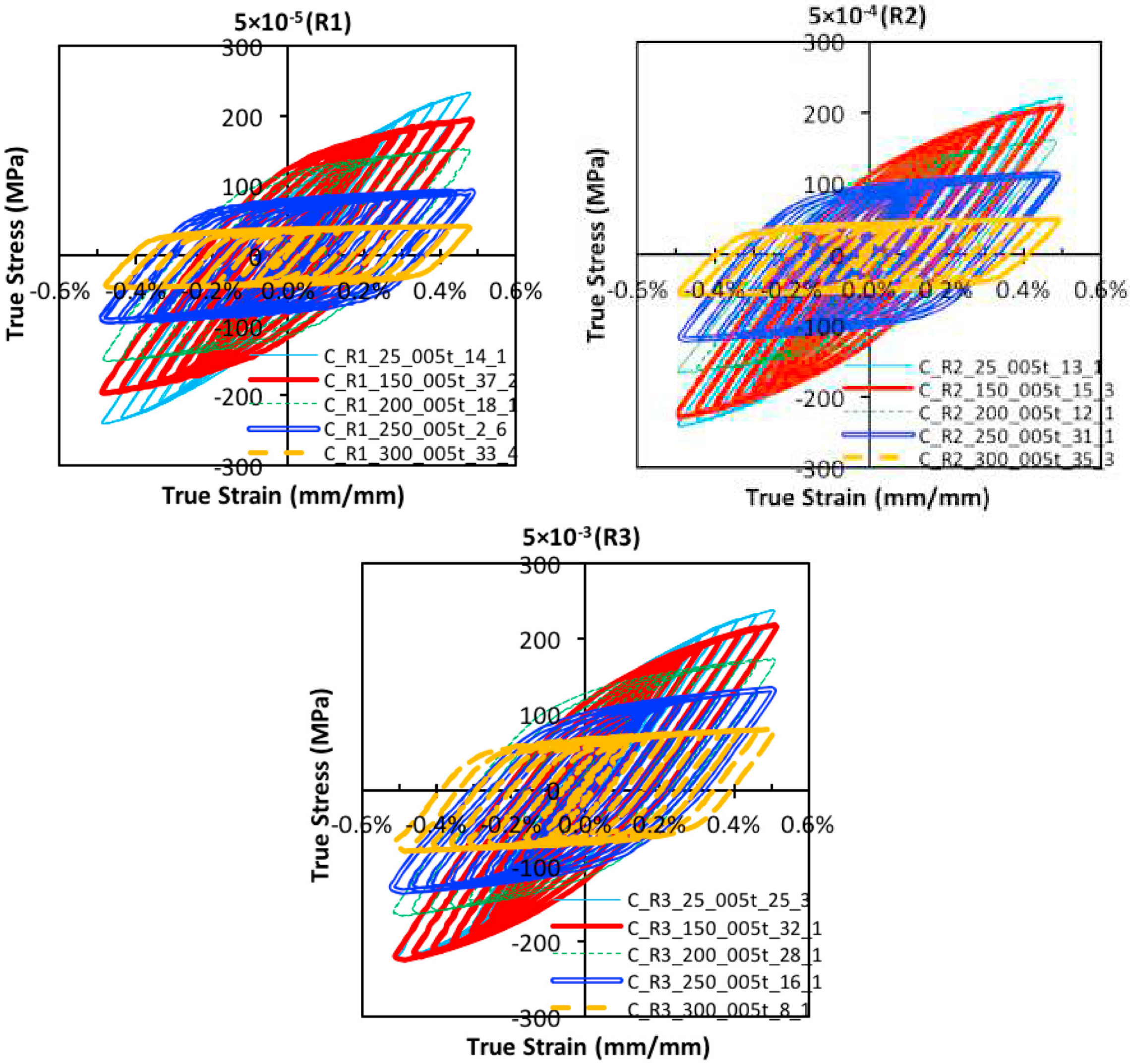


Fig. 8. Stabilized cyclic behaviors at various temperatures with strain rates of (a) 5x10^{-5} s^{-1}, (b) 5x10^{-4} s^{-1} and (c) 5x10^{-3} s^{-1}.

Figure 9 displays the strain rate sensitivity of the cyclic hysteresis loops. Though the hysteresis loops are not sensitive to strain rate in room-temperature tests, they are affected by strain rate at elevated temperature. At raised temperature, similar to monotonic tensile tests, with a larger strain rate, a higher load/stress is required to generate the same strain. The reason for this occurrence may be related to thermal softening as is described in the preceding section.

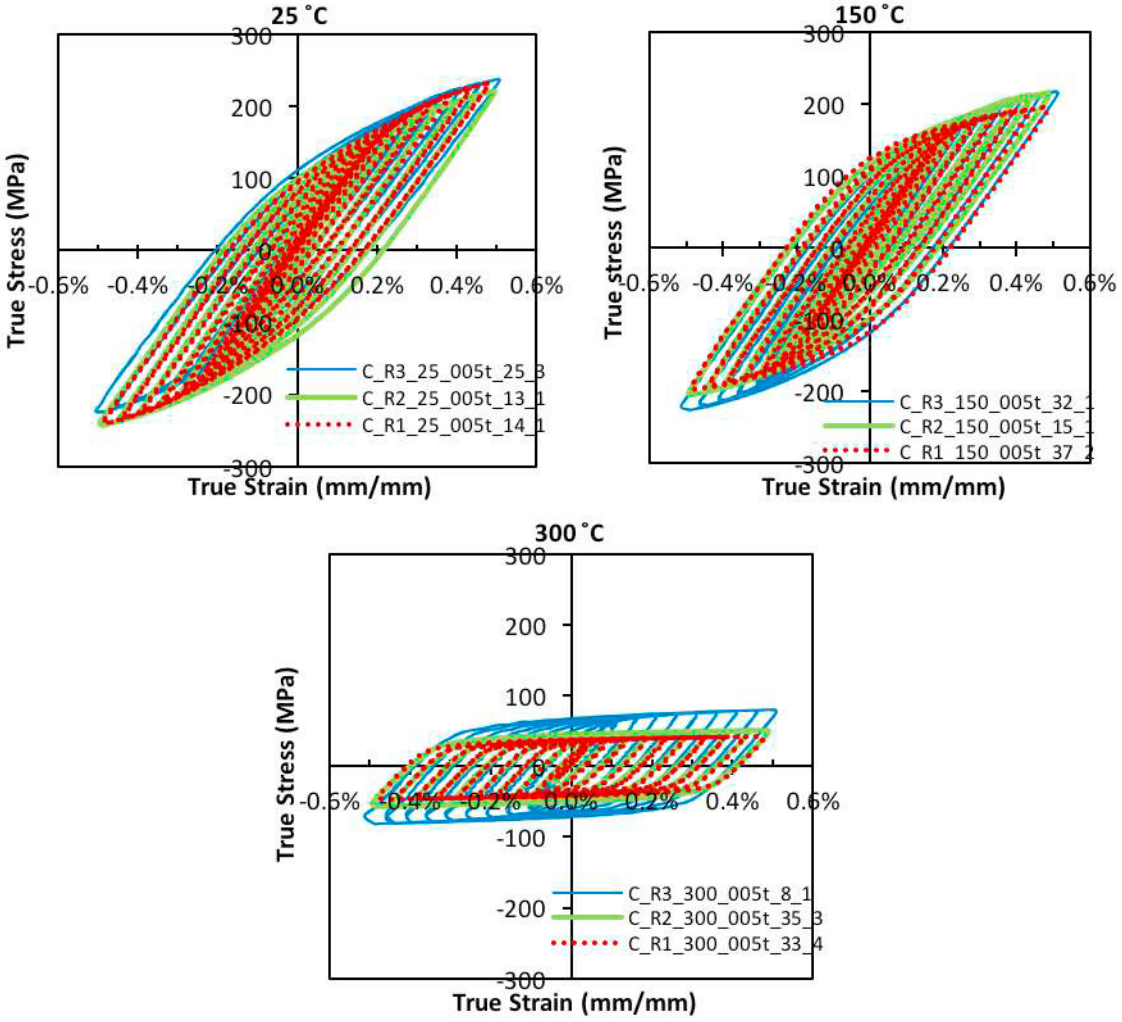


Fig. 9. Stabilized cyclic behaviors with various strain rates under different temperatures: (a) 25°C, (b) 150°C, and (c) 300°C.

3.3. Isothermal fatigue tests

In the following fatigue tests, fatigue life (i.e. cycles to failure) is defined by 50% load drop.

Test results presented with total applied strain amplitude versus number of cycles to failure are exhibited in Figure 10, from which the temperature effect is not clearly observed with the total applied strain amplitude. However, an interesting thing found is that, at the same strain amplitude, the fatigue life at 300°C is longer than the one tested below 250°C. This is mainly due to the significant stress softening that happens in the high-temperature environment, by which the fatigue life is extended.

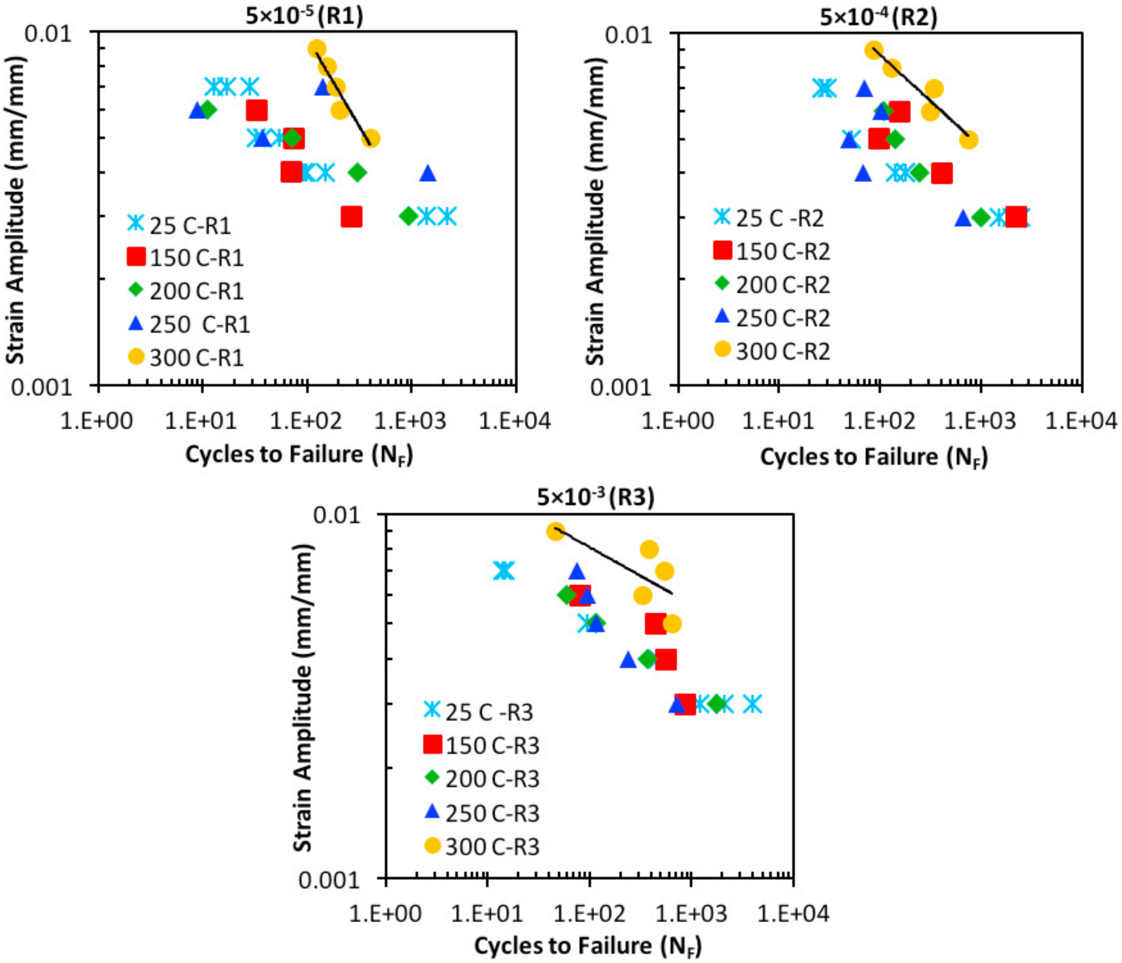


Fig.10. Strain amplitude vs. fatigue life at various temperatures with strain rates of (a) 5x10^{-5} s^{-1}, (b) 5x10^{-4} s^{-1} and (c) 5x10^{-3} s^{-1}.

The stress-life plot, Figure 11, clearly shows the effect of temperature on isothermal fatigue tests. The stress amplitude is taken at half-life cycle since no obvious stabilized cycle was discovered for the test conditions. Contrary to the strain-life plot, Figure 11 shows that the 300˚C test condition has the shortest fatigue life at the same stress amplitude compared to the other test temperatures. Moreover, higher fatigue life occurs under lower-temperature test conditions. The room-temperature test is the safest case for this material and has the longest fatigue life for all tested strain rates.

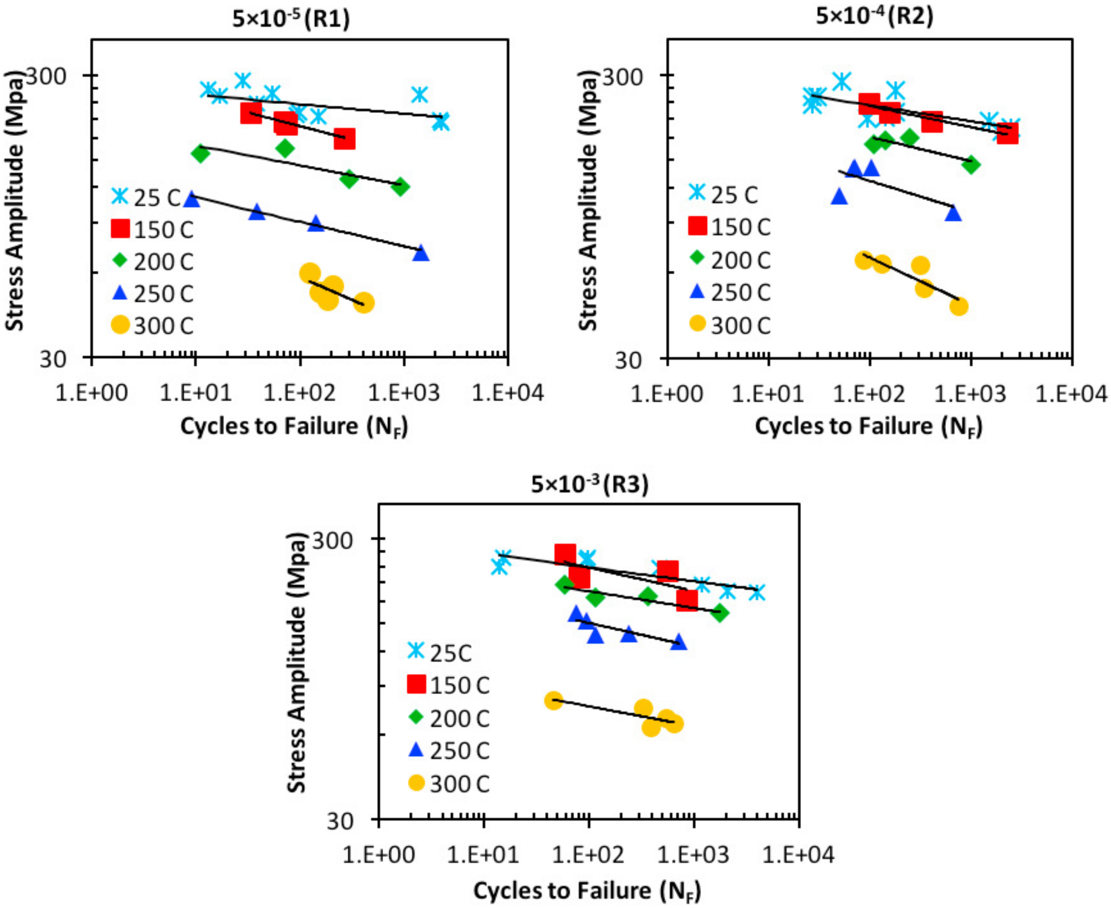


Fig. 11. Stress amplitude vs. fatigue life at various temperatures with strain rates of (a) 5x10^{-5} s^{-1}, (b) 5x10^{-4} s^{-1} and (c) 5x10^{-3} s^{-1}.

As seen in Figure 12, the strain rate effect on fatigue life in the room-temperature test is quite different from that in the high-temperature tests. While the effect of the strain rate is negligible at room temperature, it has a considerable influence in tests above 150˚C. In the high-temperature case, longer fatigue life happens with a higher strain rate, which may be explained by the shorter exposure time at high temperature resulting in less creep and oxidation damage. In contrast, a lower strain rate induces larger creep and oxidation damage in the specimen at high temperature so as to shorten the life to failure.

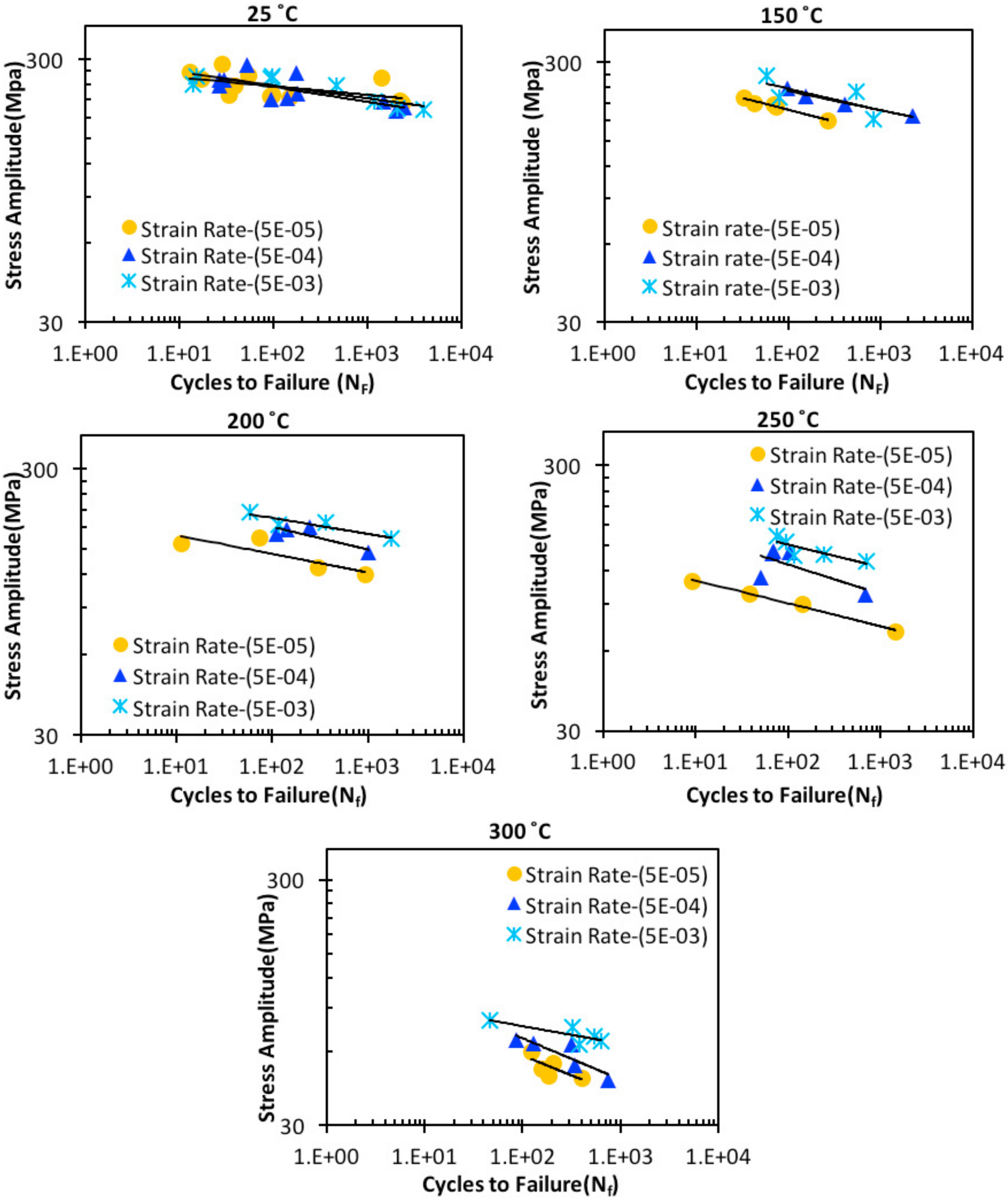
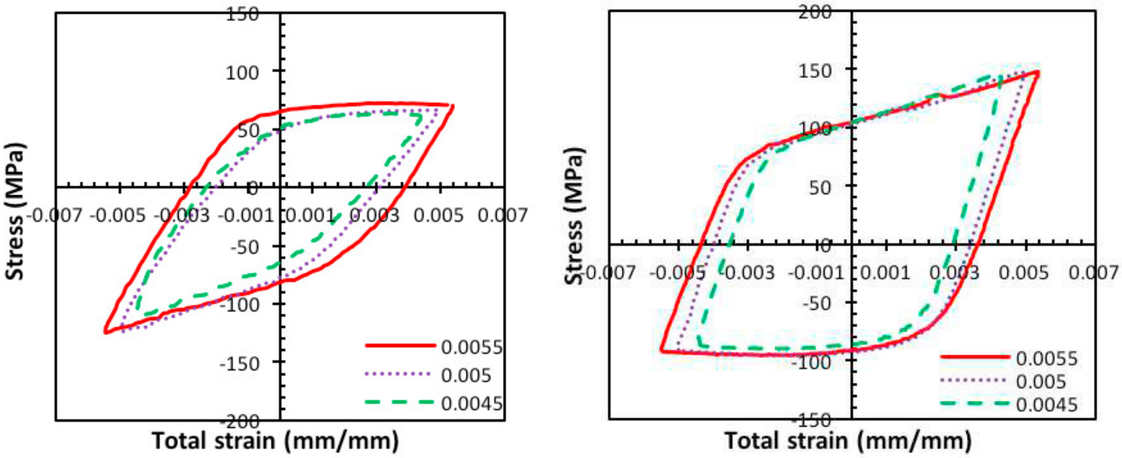


Fig. 12. Stress amplitude vs. fatigue life with various strain rates under different temperatures: (a) 25˚C, (b) 150˚C, (c) 200˚C, (d) 250˚C and (e) 300˚C.

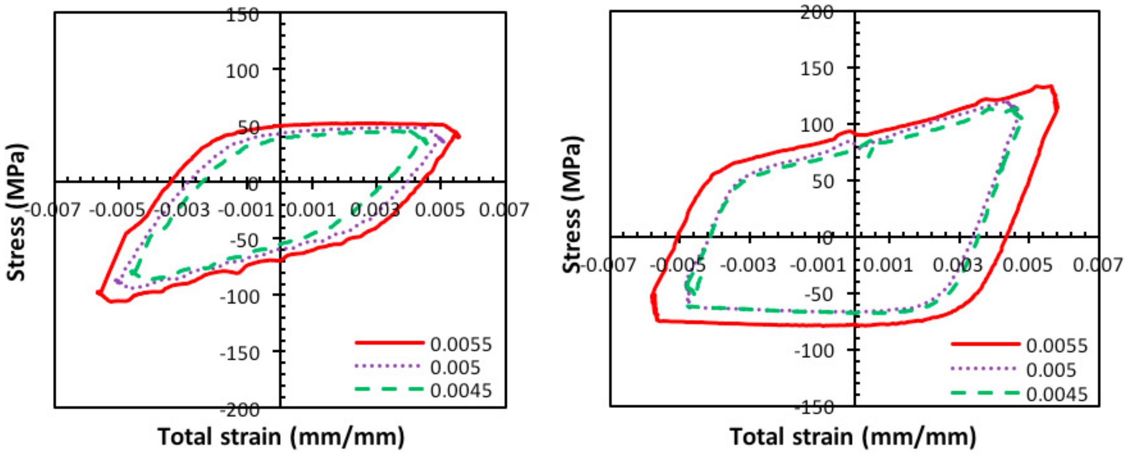
3.4. Thermo-mechanical fatigue tests

It was observed in the preceding part that the strength of this alloy is lower at 300˚C than that at 150˚C. Then, for in-phase TMF tests, which are under tensile status at high temperature, the magnitude of peak tensile stress is less than the magnitude of compressive stress, even though the specimen experiences the same amount of tensile and compressive total strain amplitude. This results in a negative mean stress in the in-phase tests and, correspondingly, a positive mean stress in the out-of-phase tests; see Figure 13.

Figure 13 also shows the hysteresis loops at different total applied strain amplitudes at the stabilized cycles for the TMF tests with dwell time, during which period obvious stress relaxation appears in both IP and OP tests.



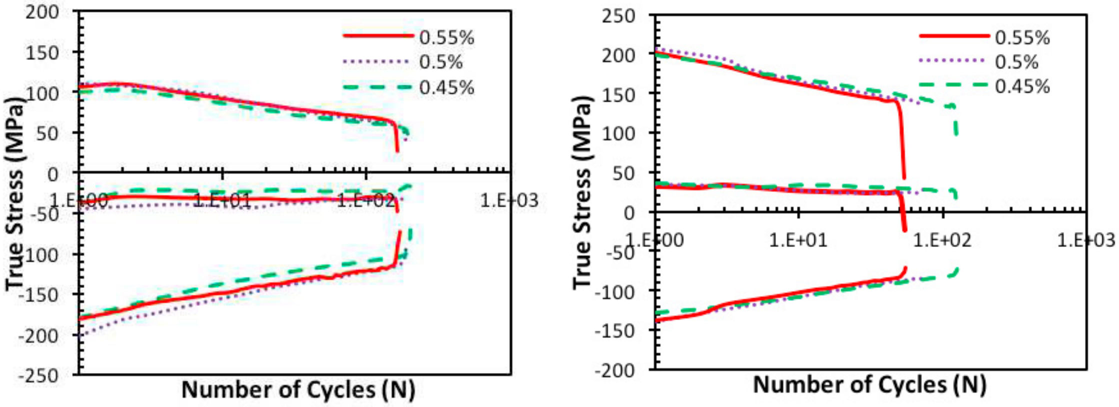
(a) IP without dwell time (b) OP without dwell time



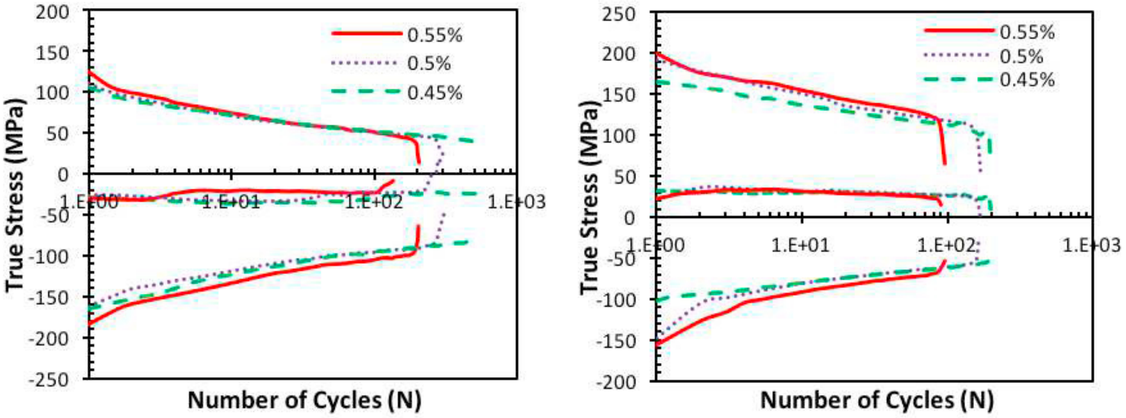
(c) IP with dwell time (d) OP with dwell time

Fig. 13. Hysteresis loops at the stabilized cycles for (a) IP loading, (b) OP loading, (c) IP loading with dwell time, and (d) OP loading with dwell time, tested at 3 different strain amplitudes.

Stress softening happens in TMF testing as also existed in cyclic and isothermal fatigue tests, which is clearly shown in Figure 14. Figure 14 agrees with the results in Engler-Pinto’s paper [2] that no stabilized cycle is found in TMF tests. Moreover, the negative and positive mean stress mentioned in the IP and OP tests, respectively, are very clear in this plot.



(a) IP without dwell time (b) OP without dwell time

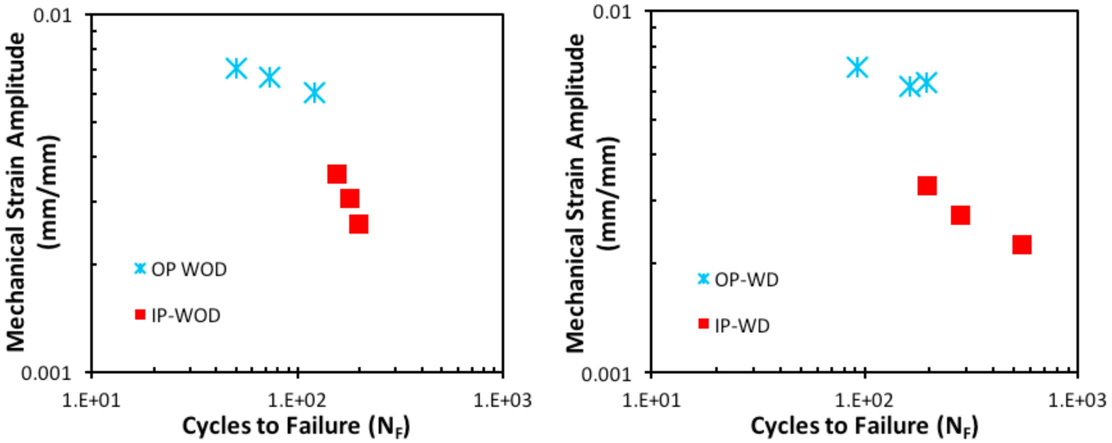


(c) IP with dwell time (d) OP with dwell time

Fig. 14. Stress variation with number of cycles for (a) IP loading, (b) OP loading, (c) IP loading with dwell time, and (d) OP loading with dwell time, tested at 3 different strain amplitudes.

From Figure 14, it is also found that the fatigue life in OP tests is smaller than that in IP tests under the same applied total strain amplitude, for both the with or without dwell time cases. This is explained by the greater mechanical and/or inelastic strain in OP tests in order to compensate for the thermal strain effect. Clearly illustrated in Figure 15, the greater mechanical strain amplitude in the OP tests results in smaller fatigue life.

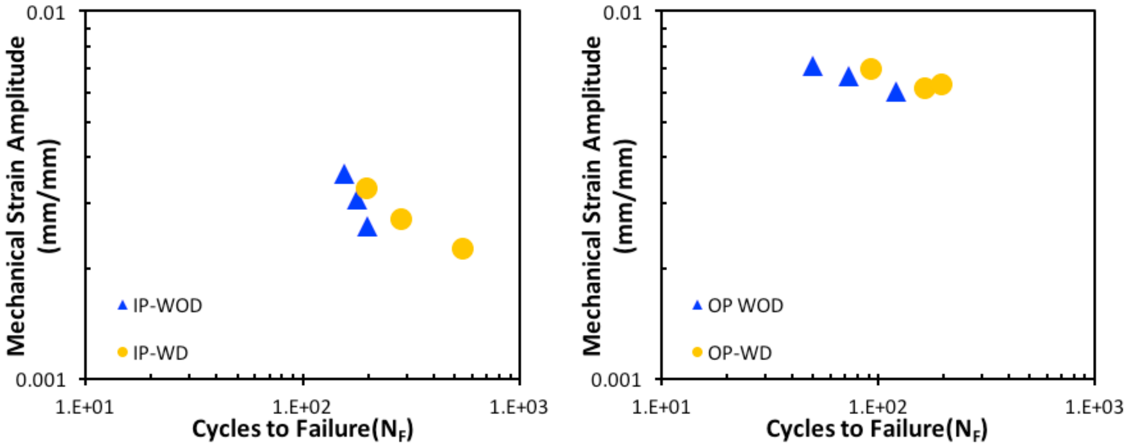
Another reason is that the tensile mean stress enacted in the OP tests usually causes life reduction, while the compressive mean stress performed in IP tests is beneficial to increased fatigue life.



(a) without dwell time (b) with dwell time

Fig. 15. Mechanical strain amplitude vs. fatigue life for TMF tests (a) without dwell time and (b) with dwell time.

Figure 16 illustrates the effect of dwell time on the fatigue life for in-phase and out-of-phase loading. Though large creep and oxidation damage may happen with dwell time, the results shown here indicate that the tests with dwell time have a longer life than those without dwell time under similar mechanical strain. Stress relaxation that happens in dwell time, as pointed out earlier, might be responsible for this phenomenon. Stress relaxation increases the life even though the plastic strain appears larger in the OP tests with dwell time.



(a) IP loading (b) OP loading

Fig. 16. Mechanical strain amplitude vs. fatigue life for (a) IP loading and (b) OP loading.

4. Conclusion

A broad experimental investigation on aluminum alloy Al319-T7 has been carried out under 5 different temperatures at various strain rates, including monotonic tensile tests, cyclic tests, isothermal fatigue tests, and thermo-mechanical fatigue tests. The influence of temperature and strain rate on the mechanical behavior has been analyzed qualitatively. The main results can be summarized as:

- In monotonic tensile tests, the yield stress and ultimate stress decrease with increasing temperature, which reflects that the material becomes “softer” under elevated temperature. Larger strain rates will produce higher stress-strain curves.

- While no obvious cyclic hardening/softening is found in cyclic tests under room temperature, the cyclic softening effect becomes more and more visible when the test temperature increases. Temperature and strain rate affect the cyclic stress-strain behavior in a way similar to how they affect it in tensile tests.
- In isothermal fatigue tests, for a given stress amplitude, higher temperature results in shorter fatigue life compared to room-temperature tests. The specimens have the longest life in room-temperature fatigue tests, under which the strain rate effect is negligible. In high-temperature tests, increased strain rates are found to improve the fatigue life.
- Under the same applied total strain amplitude, out-of-phase TMF tests are more dangerous than in-phase TMF tests for Al319-T7 due to larger mechanical strain amplitude and/or positive mean stress. The specimens tested in TMF with dwell time show a longer fatigue life than those tested without dwell time.

References

[1] Smith, Tracy J., Huseyin Sehitoglu, Eric Fleury, Hans J. Maier, and John Allison. "Modeling High-Temperature Stress-Strain Behavior of Cast Aluminum Alloys." *Metallurgical and Materials Transactions A* 30, no. 1 (1999): 133–46.

[2] Engler-Pinto, C. C., Huseyin Sehitoglu, H. J. Maier, and T. J. Foglesong. "Thermo-Mechanical Fatigue Behavior of Cast 319 Aluminum Alloys." *European Structural Integrity Society* 29 (2002): 3–13.

[3] Sehitoglu, Huseyin, Tracy Smith, Xinlin Qing, Hans J. Maier, and J. A. Allison. "Stress-Strain Response of a Cast 319-T6 Aluminum under Thermomechanical Loading." *Metallurgical and Materials Transactions A* 31, no. 1 (2000): 139–51.

[4] Engler-Pinto, C. C., Huseyin Sehitoglu, and Hans J. Maier. "Cyclic Behavior of Al319-T7b under Isothermal and Non-Isothermal Conditions." *ASTM Special Technical Publication 1428* (2003): 45–64.

[5] Su, Xuming, Michael Zubeck, John Lasecki, Huseyin Sehitoglu, C. C. Engler-Pinto, Chung-Yao Tang, and John E. Allison. "Thermomechanical Fatigue Analysis of Cast Aluminum Engine Components." *ASTM Special Technical Publication 1428* (2003): 240–54.

[6] Kang, Hong Tae, Yung-Li Lee, Jim Chen, and David Fan. "A Thermo-Mechanical Fatigue Damage Model for Variable Temperature and Loading Amplitude Conditions." *International Journal of Fatigue* 29, no. 9 (2007): 1797–802.

[7] Bae, G. H., and H. Huh. "Tension/Compression Test of Auto-Body Steel Sheets with the Variation of the Pre-Strain and the Strain Rate." *WIT Transactions on Engineering Sciences* 72 (2011): 213–25.

[8] ASTM International. ASTM E606/E606M-12 Standard Test Method for Strain-Controlled Fatigue Testing. West Conshohocken, PA: ASTM International, (2012). doi: https://doi.org/10.1520/E0606_E0606M-12.