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STRAIN-CONTROLLED THERMO-MECHANICAL FATIGUE TESTING OF ALUMINUM ALLOYS USING THE GLEEBLE® 3800 SYSTEM

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ABSTRACT

Understanding the thermo-mechanical fatigue (TMF) behavior of materials plays a significant role in the safety design of critical components used in aerospace and automotive industries, such as engine blocks and cylinder heads, which undergo the cyclic change of temperature and stress. However, the cyclic changes of temperature, stress and strain make it difficult using the traditional testing methods to accurately simulate the TMF process. In the present work, the Gleeble® 3800 system was successfully applied to develop a reliable procedure to measure the TMF behavior of aluminum alloys. The modified setup together with the new designed program allows the Gleeble system to precisely simulate the cyclic profiles of temperature and mechanical strain. The novel procedure includes the calibration and verification of the TMF setup to ensure the test validity with Young's modulus measurement, multi-cycle measurement of the thermal strain and zero stress adjustment followed by online monitoring the TMF cycles. The results of the TMF testing of an AA6061 alloy under cyclic temperatures (60–300°C) and various strain amplitudes (0.2–0.6%) were demonstrated. Its TMF behavior was characterized by the typical hysteresis loops and cyclic stress-strain response.

KEYWORDS

Thermo-mechanical fatigue, Gleeble® 3800 system, Fatigue test method, AA6061 aluminum alloy, Hysteresis loop

INTRODUCTION

The thermo-mechanical fatigue (TMF) behaviour becomes increasing important to evaluate the elevated-temperature properties of materials used as the critical components in automotive and aerospace industries, such as the gas turbines (Hu, Shi & Yang, 2016; Moverare, 2007; Segersäll et al., 2015) and engine blocks (Grieb, Christ & Plege, 2010; Javidani & Larouche, 2014). During the cycles of start-up and shutdown of the engines, these components undergo a complex change of loading. Meanwhile, a dramatic temperature gradient exists on the components due to the cooling system. Therefore, the cyclic changes of load and temperature can give rise to the TMF and may limit the use life of such components (Hu, Shi & Yang, 2016; Javidani & Larouche, 2014; Moverare, 2007). Hence, performing the TMF tests to precisely simulate the cyclic changes of load and temperature to understand the TMF behaviours of materials is playing a significant role in the safety design of these components. For TMF tests, two principal types of cycles are generally employed, including the in-phase (IP) cycle where the load and temperature are at the same phase (i.e. maximum load at highest temperature) and out-of-phase (OP) cycle where the maximum load is applied at minimum temperature (Kliemt, 2012; Miller, 2014). The most significant damage mechanisms in engine components are reported to be OP TMF cycles (Javidani & Larouche, 2014; Kliemt, 2012).

Though the code-of-practice for strain-controlled TMF tests is suggested (Hähner et al., 2008), there are still many challenges in realizing and controlling the cyclic changes of temperature, stress and strain during the TMF tests under the commonly used methods, such as the tests performed on traditional tensile test union with the aid of induction coil (Hu, Shi & Yang, 2016; Moverare, 2007; Segersäll et al., 2015), in which the controlling of the cyclic change of temperature and the homogeneous distribution of temperature are still difficult. In addition to the numerous research works in the hot deformation of various metals, the Gleeble® thermal-mechanical simulator system is also reported to be a useful tool to get the thermal-mechanical properties of carbon-based materials (Racine et al., 2015). The Gleeble system has excellent capacities to simultaneously control the temperature, stress and strain over the testing sample, which is the essential for different kinds of thermal or TMF tests. However, limited research for its application in TMF tests of metals and alloys has been performed.

The aim of the present work is to develop the new procedure using the Gleeble system to precisely measure the TMF behaviour of aluminum alloys with modified setup together with the new designed program. Meanwhile, the TMF properties of an AA6061 aluminum alloy under cyclic temperatures (60–300°C) and at various strain amplitude (0.2–0.6%) were measured with this procedure and its behavior was characterized by the typical hysteresis loops, cyclic stress/strain response and TMF life assessment.

THE GLEEBLE 3800 SYSTEM FOR THERMO-MECHANICAL TESTING

The Gleeble 3800 system, shown in Figure 1, is a thermo-mechanical physical simulator that can replicate a material working or manufacturing solicitations in a gas/vacuum tight chamber. It has already shown good testing versatility with a variety of options like low force jaw carrier, cooled extensometer, multi-thermocouple monitoring, multi-medium quenching system, etc. The most remarkable feature of this system is its Joule’s heating system. Unlike induction heating that only generates skin-deep heat, the Gleeble 3800 system directly produces heat throughout the sample’s volume, generating low radial and axial gradient in the sample’s gage length. Combined with the system low thermal inertia, it gives fast and uniform heating for reliable and low dispersion results.

Figure 1. Overview of Gleeble 3800 thermo-mechanical physical simulator system

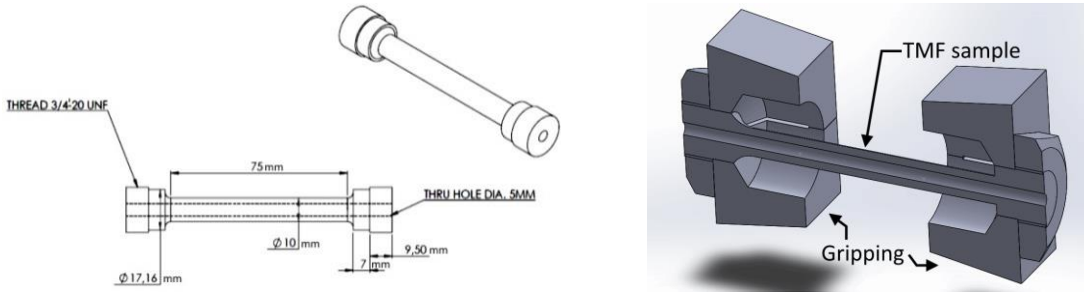
Another essential component of the Gleeble 3800 is its programming flexibility with the optional Gleeble Script Language (gsl) that allows the user to conveniently design the program according to the customer demand. With the help of Excel interface, it is possible to build a TMF programs with all relevant testing parameters including test limits, sample information, temperature profile, acquisition scheme and PIDs settings. It also allows live display of current cycle data like cycle number, min/max stress and total stress drop that can be saved in a separate file for easier analysis. These characteristics can well fit the stringent need of strain-controlled TMF testing (ASTM International, 2010; Hähner et al., 2008), which are:

1) Accurate temperature control;
2) Adequate heating and cooling capacity in a relatively short cycle;
3) Accurate measurement of strain and stress;
4) Stable and repeatable loop control for temperature, strain and stress over a long period of time.

PREPARATION FOR TMF TESTS

Sample Geometry

In order to meet the requirements of TMF tests in the Gleeble system, there was a need to redesign the sample geometry to get the most out of the system capacity while staying close to desirable thermal cycle. Considering constraints, such as sample's blank dimension, average grains size, gripping setup, total displacement and space restriction, the final sample geometry and dimension were chosen as shown in Figure 2 (ASTM International, 2010). The hollow tube sample can allow the air flow through the tube, giving the uniform cooling with minimal thermal gradient that does not disturb the environment and avoids the uneven cooling and the disturbance of measurements (extensometer noise and thermocouple failure). For the thread, the length and type were chosen to be as small as possible while being able to bear the maximal force of tests with a security factor. 2.5 mm of wall thickness was designed to accommodate an average grain size of up to 250 μm of aluminum foundry alloys. Finally, the gage length was maximized from the blank dimension to give a low axial thermal gradient while leaving enough displacement room for completing the test.



(a) (b)

Figure 2. TMF sample dimensions used (a) and the setup with gripping blocs (b).

Temperature Profile Control

In the present work, the temperature range of TMF tests is between 60 and 300°C. Figure 3 shows the temperature profiles measured at 60 and 300°C near the gage zone of the sample. It can be found that the temperature gradient is very small in the gage zone, which is in ~2% at the maximum temperature of 300°C (Figure 3a) and ~ 5% at the minimum temperature of 60°C (Figure 3b). Therefore, the temperature control is precisely succeeded on Gleeble TMF samples.

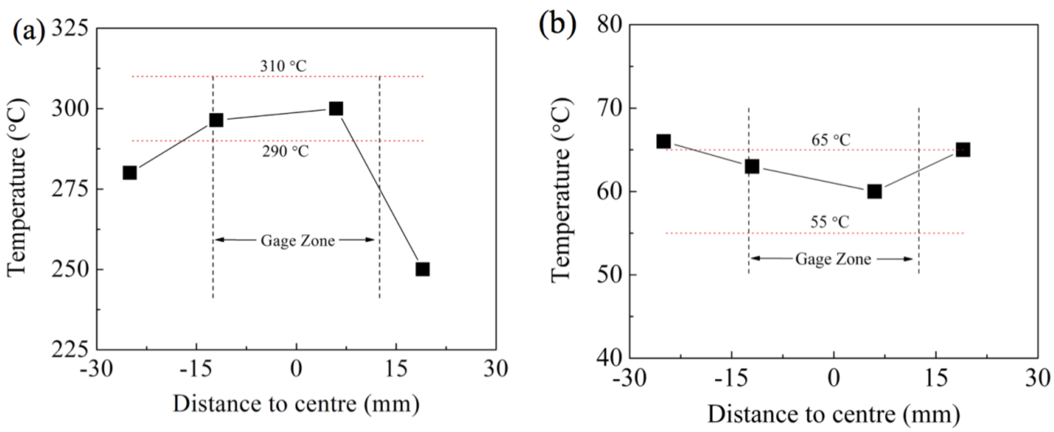


Figure 3. Temperature profile near the gage zone along the sample long axis at (a) 300°C and (b) 60°C.

Pre-Tests

Before actually performing the strain-control TMF tests, there are a series of validation procedures, which are mainly composed of the sample installation, Young's modulus measurement, multi-cycle measurements of thermal strain and the zero stress adjustment.

The installation begins with the sample size measurement followed by the surface cleaning with soda powder to remove the oxidation layer before spot-welding thermocouple in order to guarantee the good connection between the thermocouple and sample. The weld is placed in the middle of the gage length instead of the outside (Hähner et al., 2008) for lag-free temperature control. After the welding, the sample is carefully placed inside its gripping blocs and put inside the chamber with the quenching accessories and then it is tightened under ~3 kN preload. For newly testing materials and sample geometries, multi-thermocouple installation and monitoring along the sample long axis are recommended. Finally, the thermocouple(s) is connected and the extensometer is installed.

The validation of the sample installation is also performed through measurement of Young's modulus at room temperature 3 times. When necessary, the Young's modulus of the sample is measured at different temperatures, e.g. T_{room}, T_{min} and T_{max}. During the process, the validation is passed when the Young's modulus remains within ±10% of the expected value.

During strain-controlled TMF tests, the total strain is programmed as command input and monitored during the cycles. It consists of thermal and mechanical strains (Eq. 1). However, only the mechanical strain is closely related to the TMF behavior. Therefore, it is significant to measure the thermal strain under zero stress during temperature cycles, which is a critical step to ensure that the thermal strain during cycling is correctly accounted for.

$$\varepsilon_{total} = \varepsilon_{therm} + \varepsilon_{mech} \tag{1}$$

To determine the thermal strain as a function of the temperature, a certain number of thermal cycles (~10–15) are carried out in stress control mode at zero stress using the same temperature-time cycle as in the actual TMF test. Before doing it, the program starts a thermal holding of 30 min at half temperature amplitude to stabilize the setup and to limit thermal drifting. Then it begins to run first few cycles to reach dynamic thermal equilibrium between the sample and gripping setup. To accurately measure ε_{therm}(T), the program divides the thermal cycle into 14 segments during heating and cooling ramp. Continuing several thermal cycles, the individual ε_{therm}(T) are obtained as average values from the measured thermal strain values in each segments with those passing cycles.

The system is then switched from the stress-control to strain-control mode for another several thermal cycles for the zero stress adjustment. The obtained ε_{therm} values are added to ε_{mech} to get the ε_{total} since the strain-controlled TMF test is controlled according to the ε_{total}. In an ideal case, this thermal strain compensation should give an average stress cycle of zero without peaks, which is very rare. To approach the zero stress, a strain correction based on Eq. 2 is applied on each of 14 segments with a reduction factor of 0.75 to avoid over tuning. This correction loop is repeated in the following thermal cycles until the average residual stress of each segment stay within 5% of expected min/max stress. Figure 4 gives an example of temperature and stain sequence in an OP TMF cycle.

$$\varepsilon = 0.75 * \sigma_{residual}/E \tag{2}$$

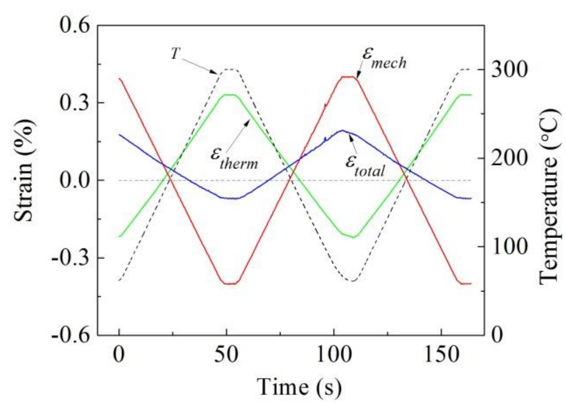


Figure 4. Example of temperature and stain sequence in an OP TMF cycle (T=60–300°C, mechanical stain amplitude 0.2% and AA6061 in annealed condition)

TMF TEST EXECUTION

After successful completion of all the pre-tests, the TMF test with the predefined heating and cooling ramp (currently between 60 and 300°C) can be started. During the TMF test, the strain, stress and temperature are monitored by the program. The TMF data for each strain amplitude (usually 0.1 to 1% for aluminum alloy) are recorded for further analysis. The TMF test is terminated when a predefined criterion is reached, e.g. a pre-set number of cycles or a drop of 30–50% in initial min/max stress.

Figure 5 shows one example for the TMF data under the mechanical strain amplitude of 0.4% in the 2nd TMF cycle using an AA6061 extruded material. Figure 5a shows temperature-strain curves (including all the strain components) during a thermal cycle. The total stress-strain curve is measured by the Gleeble system (Figure 5b) and the mechanical stress-strain curve (Figure 5c) is calculated by subtracting the thermal strain from the total strain according to Eq. 1.

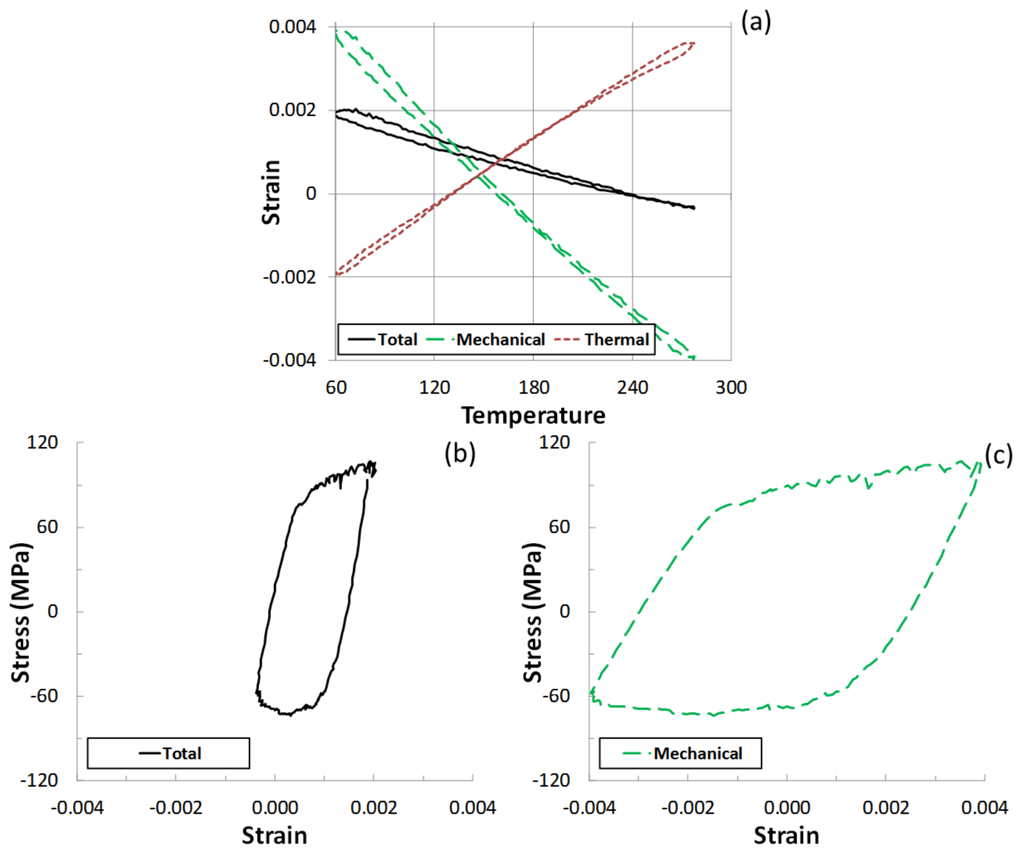


Figure 5. The temperature-strain curves (a), the total strain-stress curve (b) and the mechanical strain-stress curve (c) under the strain amplitude of 0.4% during the 2nd cycle.

TMF RESULTS AND DATA ANALYSIS OF AN AA6061 ALLOY

In the present work, a commercially available extruded AA6061 rod material (nominal composition: 0.63 wt.% Si, 0.85 wt.% Mg, 0.26 wt.% Cu, 0.25 wt.% Fe) was used for the TMF tests. Before testing, an annealing treatment (300°C/8h) was performed on the AA6061-T651 to stabilize the material condition. The out of phase (OP) TMF tests were performed based on the accepted code-of-practice (Hähner et al., 2008) and ASTM E2368-10 standard (ASTM International, 2010), where the mechanical strain is maximum at minimum temperature. The loading condition of TMF test under 0.2% mechanical strain amplitude measured at the late stage of testing (900th cycle) is shown in Figure 6. In general, the temperature and mechanical cycles are very stable and precisely followed even at very late stage of testing, confirming the good performance of Gleeble TMF tests.

A series of TMF tests were performed at temperatures between 60 and 300°C and at three mechanical strain amplitudes (0.2, 0.4 and 0.6%). Stress-strain hysteresis loops for the 2nd, mid-life and final cycles at specified strain amplitudes are illustrated in Figure 7. It can be found that the mechanical strain of these loops were well controlled with predefined strain amplitudes in all cycles, confirming the reliability of TMF tests in the Gleeble system. For the evolution of hysteresis loops during the TMF cycles, it is observed that the loops at 0.2% are generally symmetrical, as shown in Figure 7a. However, the hysteresis loops is losing the symmetricity with increasing strain amplitude, in which the tensile and compressive stresses exhibit different behaviors. This is more obvious at higher strain amplitude, such as at 0.6% in Figure 7c, where several mechanisms such as the strain hardening, creep and coarsening of metallurgical phases have different kinetics depending on temperature (Javidani & Larouche, 2014).

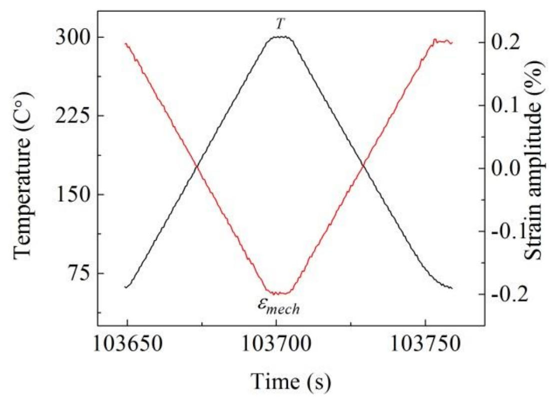


Figure 6. The OP loading condition with 0.2% strain amplitude at the 900th cycle.

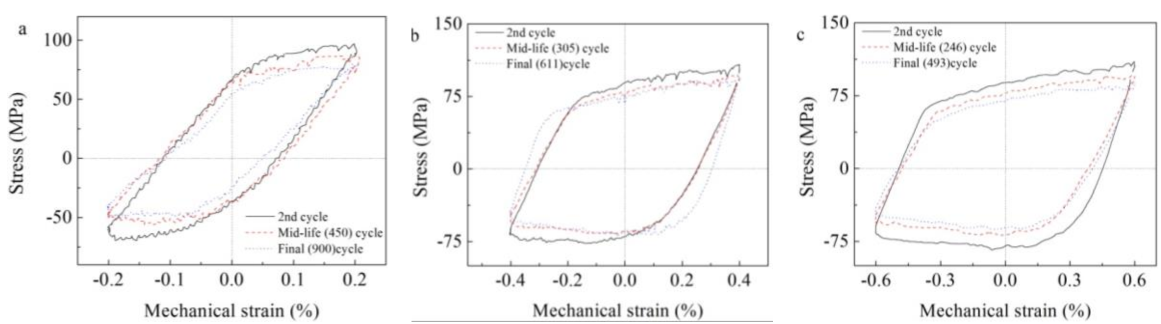


Figure 7. Stress-strain hysteresis loops at mechanical strain amplitudes: (a) 0.2%, (b) 0.4% and (c) 0.6%

In order to compare the TMF behaviors at various strain amplitude, Figure 8 shows the cyclic stress-strain hysteresis loops at the 2nd cycle and mid-life cycle at three strain amplitudes. The cyclic evolution of maximum tensile stress and minimum compressive stress at three strain amplitude during an entire test are presented in Figure 9. As shown in Figure 8, the absolute value of maximum/minimum stress increases with increasing strain amplitude. The cyclic softening is generally observed in all strain amplitudes studied, in which the maximum tensile stress decreases while the minimum compressive stress increases with increasing cycles, as shown in Figure 9. However, the softening rate of maximum and minimum stress with strain cycles increases with increasing of strain amplitude.

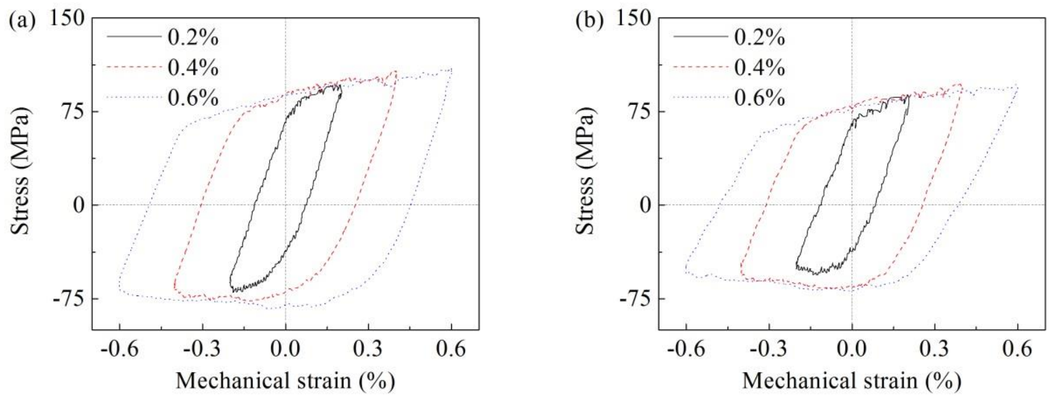


Figure 8. Hysteresis loops at (a) 2nd cycle and (b) mid-life cycle under three strain amplitudes.

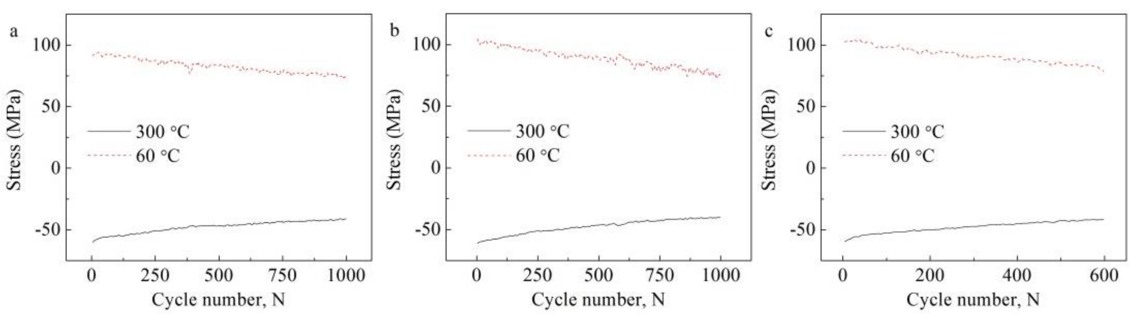


Figure 9. Variation of maximum and minimum stress from tests under: (a) 0.2%, (b) 0.4% and (c) 0.6% strain amplitude vs. number of cycles.

Since there was no sharp drop on the stress curve with this material condition during TMF test, the TMF life here was defined at the cycle when the stress falls by 30% below the initial min/max stress. Accordingly, the TMF life of studied AA6061 alloy at 0.2%, 0.4% and 0.6% strain amplitude are 900, 611 and 493 cycles, respectively, showing the decreasing TMF life with increasing strain amplitude.

CONCLUSIONS

In the present work, the Gleeble 3800 system was successfully adapted to develop a reliable procedure to measure the TMF behavior of aluminum alloys. The novel procedure includes the calibration and verification of the TMF setup and sample to ensure the test validity with Young's modulus measurement, multi-cycle measurement of the thermal strain and zero stress adjustment followed by the online monitoring the TMF cycles. The results show that the Gleeble system with modified setup and newly designed program can reliably perform the TMF tests due to their excellent capability of dynamic temperature, stress and strain control. The strain-controlled OP TMF tests of an AA6061 alloy under cyclic temperatures (60–300°C) and various strain amplitudes (0.2–0.6%) were successfully performed. Its TMF behavior was characterized by the typical hysteresis loops, cyclic stress-strain response and the TMF life assessment.

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