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Software Evolution to Support Advanced Mechanical Testing Methods: An Application Example of Thermo Mechanical Fatigue Testing

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Abstract

The major improvements in mechanical testing systems rely on development in software usability and flexibility. In the case of Thermo Mechanical Fatigue (TMF) testing, we must take into account a number of different parameters and algorithms for all aspects of investigation that are defined in a standard definition , called “validated code of practice for strain controlled thermo mechanical fatigue testing”. New software implements this code of practice by following all the individual steps: thermal control stability, zero stress test, modulus calculation, thermal strain measurement, test execution and reporting. Examples are given on how to perform thermal strain compensation calculations with basic formulas or advanced algorithms using an open source programming language called Python. Further, an adaptable display allows the user to choose what information to show at what point in time. The complete test procedure is defined in a fully open environment with the possibility to modify any of the individual steps or calculations. Results are given on thermal strain measurement, modulus calculation and temperature gradient control.

Key words: fatigue, mechanical testing systems, thermo mechanical fatigue, thermal strain, MTS TestSuite, temperature gradient, zero stress test

1. Introduction

Mechanical testing of sample materials already existed in the late 17th century. Robert Hooke made first experiments in 1675 and produced his law “ut tension sic vis” in 1678. In 1734 French J Le Roy invented the first dynamometer. Scientists developed progressively through the years specific tools to measure the mechanical properties they needed. Depending on their application, different technologies appeared, many of which are still valid today. A user interested in the highest accuracy within the low force range will prefer electromechanical systems while an application of higher forces or higher frequencies will use a servohydraulic technology. Recently, servo-electric machines came into use as an attempt to remove the use of oil at high frequencies, but this technique is limited to a specific load range which often excludes the possibility to work on metallic samples.

Nevertheless, the fundamental application of mechanical testing has not changed during the last century beyond the gripping of a specific geometry and pulling on it to measure fundamental material properties. However, users are interested to introduce flexibility to study domains as the viscoelastic behavior of materials or fatigue and fracture mechanics. The need of temperature measurement with simultaneous application of accurately controlled force, displacement or strain required the introduction of specific electronic controllers. The evolution of these controllers was previously described [1], specifically for analog and digital devices. These controllers work in association with software to reach the necessary flexibility required by the evolution of science. We consider in general two different software layers, the first one being used for different test system components to communicate with each other, transparent to the user, and the second one which is the men/machine interface. This last item is of critical importance in terms of ease of use and application potential on a given test system.

So a significant part of the development efforts provided by instrumentation companies today focuses on the software and its capability to give the user near limitless power of adaptation to a wide range of testing scenarios. MTS Systems regularly launches new tools to increase this flexibility. This paper describes a new implementation of a TMF (Thermo Mechanical Fatigue) testing procedure.

2. The Thermo Mechanical Fatigue Testing Code of Practice

In an attempt to create a standard for TMF testing, a document called code of practice [2] has been created by a consortium of international partners. The goal is to consistently characterize materials subjected simultaneously to thermal and mechanical loads. The methods consist of applying a given strain to the material depending on a cyclic stress. Ultimately, the specimen failure is analyzed depending on the number of cycles applied. One of the difficulties in this test is due to the fact that the total strain is the sum of a thermal strain and a mechanical strain. The phase shift which can be generated between temperature induced and mechanically induced strain open the door to a number of different material behavior interpretations. For this reason, the code of practice reduces the phase shift command to two possibilities, the in phase (maximum strain at maximum temperature) and the out of phase (maximum strain at minimum temperature) cycling. This complex test is described in Figure1, which includes all the necessary steps from the calibration to the data reporting.

Of course, advanced research institutes do not limit themselves to the application of this code of practice. As an example, some of them want to vary the phase relationship between mechanical and thermal strain. This requirement is not discussed in this paper as we want here to keep the code of practice as the guide line. Nevertheless, the software includes this level of flexibility.

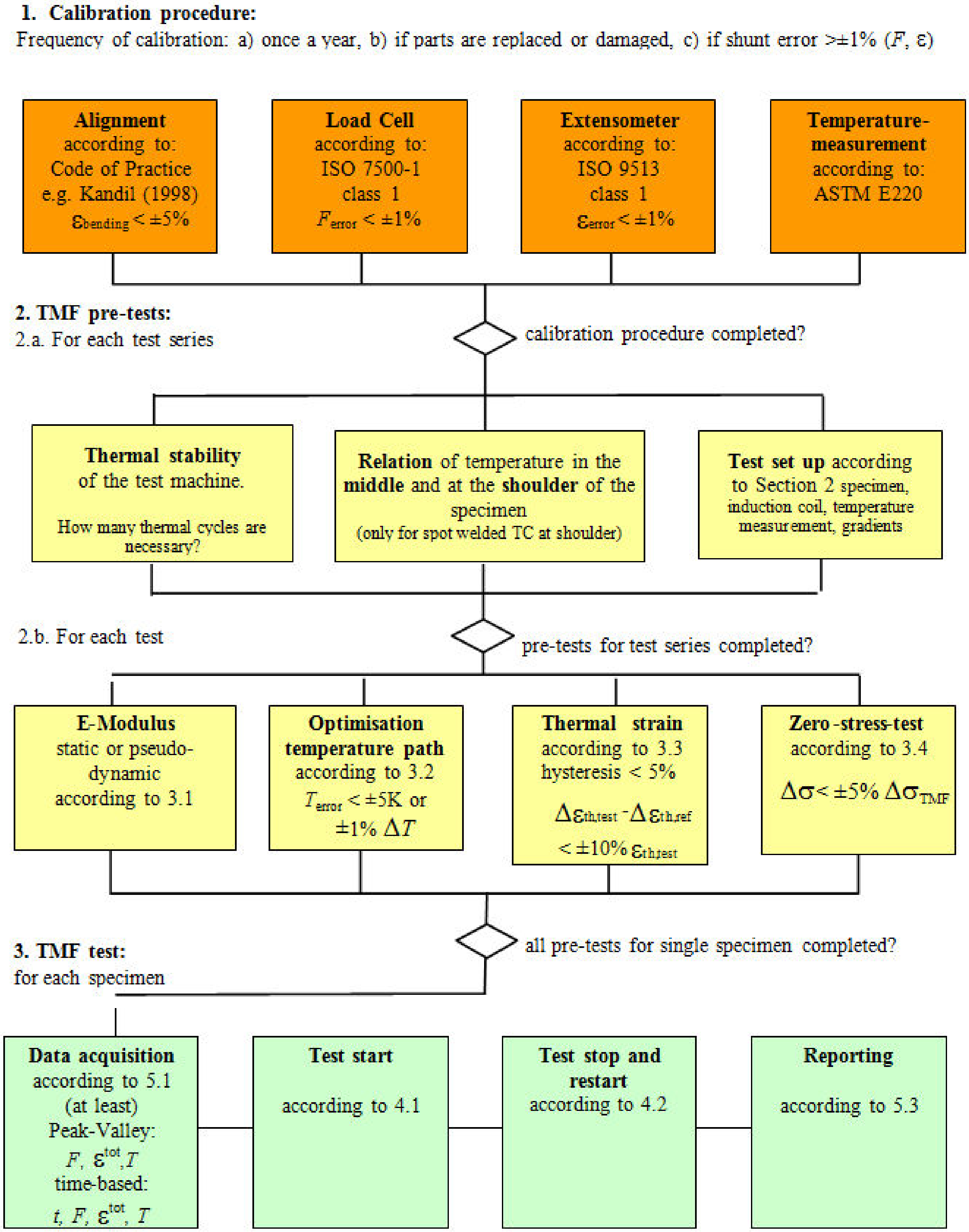


Figure 1: TMF Code of Practice

The following sections describe the most important aspects of the test template to conduct the tasks as outlined in the code of practice.

2.1 Command Panel

Each step is available on a main panel facing the user. This panel is composed of different buttons [Figure2] which execute the desired part of the procedure.

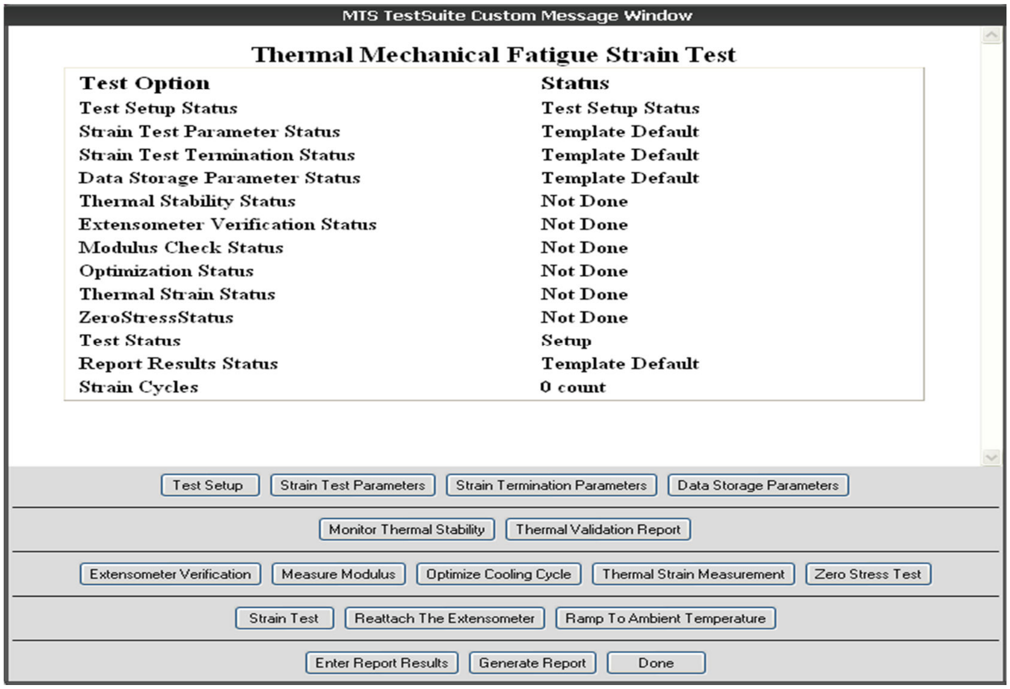


Figure 2: Command panel of the TMF template

Each button corresponds to part of a block diagram which commands a given procedure. Most of these procedures are independent, which means that the user decides which ones he wants to perform and in which order. The “Measure Modulus” button for example, generates a load-unload ramp and compares the measured modulus with the theoretical value entered in the specimen definition process.

The complete procedure is then divided in the major steps accessible with the buttons (Thermal Stability Monitoring, Thermal Strain Measurement, Zero Stress Test, Strain Test,…) and can be repeated as desired.

With this tool, the user can create or modify his own sequence (which action to generate and how) and also define the complete design of the test. The button relates a variable to a diagram block or a single activity. In the case of elaborate templates, the different action blocks are controlled with one variable associated to a choice list.

In the TMF template the different blocks are linked through a variable called “Test Prompt Answer” associated with a choice list of 15 items [Figure3]. This design implements complex test procedures without requiring the user to program anything. When the user presses a button, it relates the corresponding action to the variable and activates the block(s) needed.

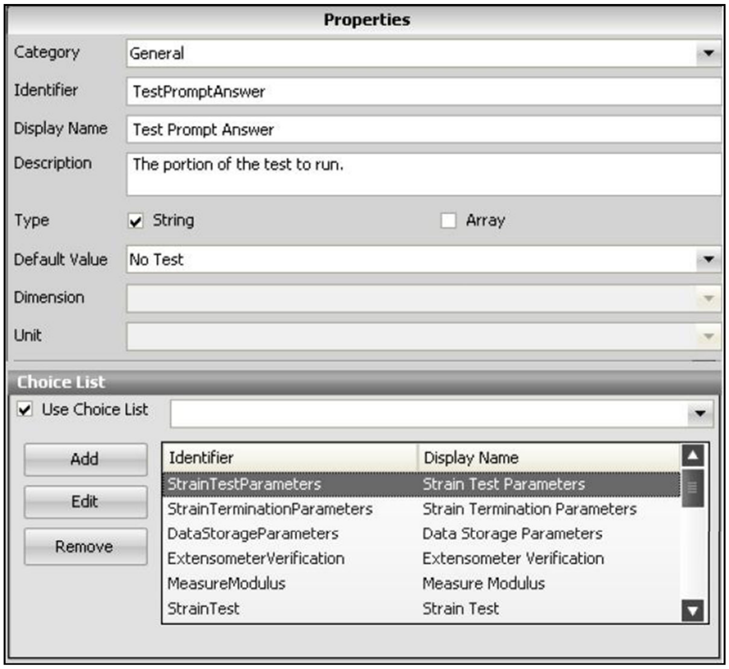


Figure 3: Variable Definition Panel

2.2 Thermal Control and Stability

The code of practice specifies that, on the one hand, the heating and cooling rates must be as low as possible and on the other hand, that the temperature gradient should be the same rate for heating and cooling.
An interesting way to do this is to calculate the temperature ramp time independently of the absolute temperature value. One way to express this is shown here:
(requested value of the temperature - the actual real temperature) / requested heating or cooling rate.

With a calculation editor [Figure4], the user can program it as follows:
abs(TemperatureCommandMean-Signal("Specimen Temperature"))/TemperatureRampRate

The formula is checked by the system which detects if it is valid or not. Each variable used in the formula can be defined in different ways. It can be a single value, or an array of data and/or the result of a previous formula. The principle of variables offers a large spectrum of flexibility to create one's own algorithm which can be updated at any moment, before or during the test.

In our example, the “thermal stable command branch” can now be composed of a ramp to zero load then a ramp to the mean requested temperature and finally a cycling activity to check the thermal stability [Figure5].

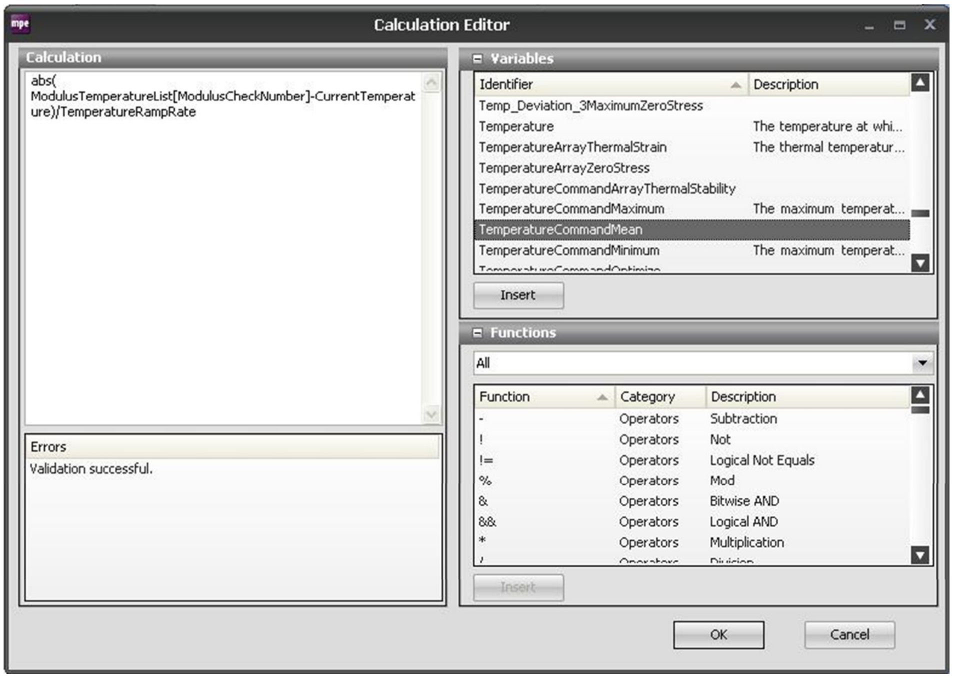
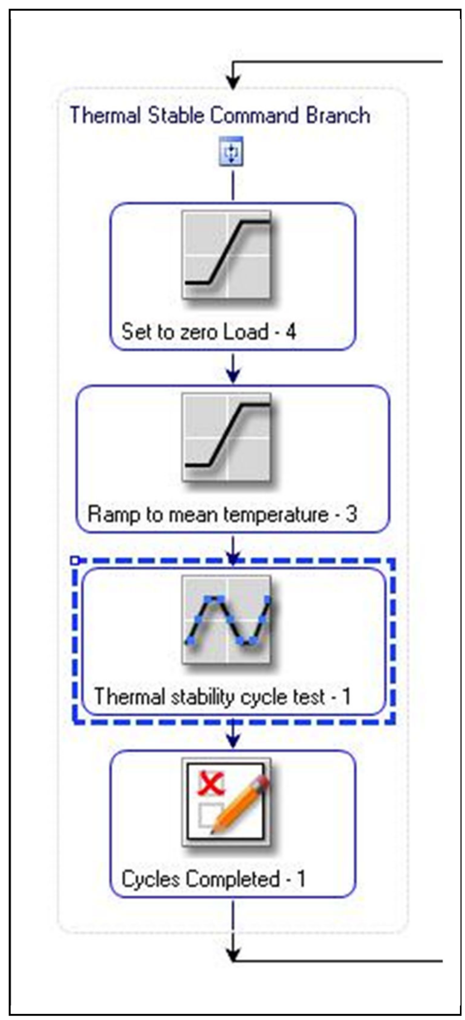


Figure 4: calculation editor

Figure 5: Thermal stable command branch



The thermal stable cycle is composed of four branches which check a possible external stop, plot the data which are out of range, check any alarm from the RF generator used to heat the sample and the thermal stable command branch which generate itself different activities to ensure the system is in proper conditions to start the stability cyclic test.

These activities which can be seen in the figure consecutively set the load to zero force then ramp the temperature to the mean value and start the cycling test activity.

Finally, the assign value activity sets the corresponding variables to indicate that this part of the TMF test is completed.

2.3 Thermal Strain

The thermal strain determination is of critical importance in a TMF test. For this reason, a zero stress test is necessary prior to each individual test. This zero stress test maintains a zero load and allows the verification of the thermal strain compensation.

Assuming the temperature control loop is optimized via suitable hardware, the user can focus on the thermal strain measurement.

The code of practice specifies that the thermal strain, obtained from the load free thermal strain measurement, must be compared and stay within a reasonable range to an external technique: e.g. dilatometry, and the maximum hysteresis should not exceed 5%

It's necessary, nevertheless, to compensate the thermal strain. This compensation can be temperature or time based.

In the case of temperature compensation, the data are fitted with a polynomial algorithm.

To realize this, MTS has developed a specific technique to calculate the thermal strain curve. This technique uses a tool, called "polynomial array", and allows one to specify the power of the polynomial. The strain temperature curve is then fitted with this polynomial.

It is well known that advanced users want to control the method each point is calculated and modify it depending on their need. To answer to this request, MTS has implemented an open source programming language, called Python, which gives the possibility to adjust and create any kind of calculation trough function generation. In the following example, the polynomial array calculation is accessible and can be modified [Figure 6].

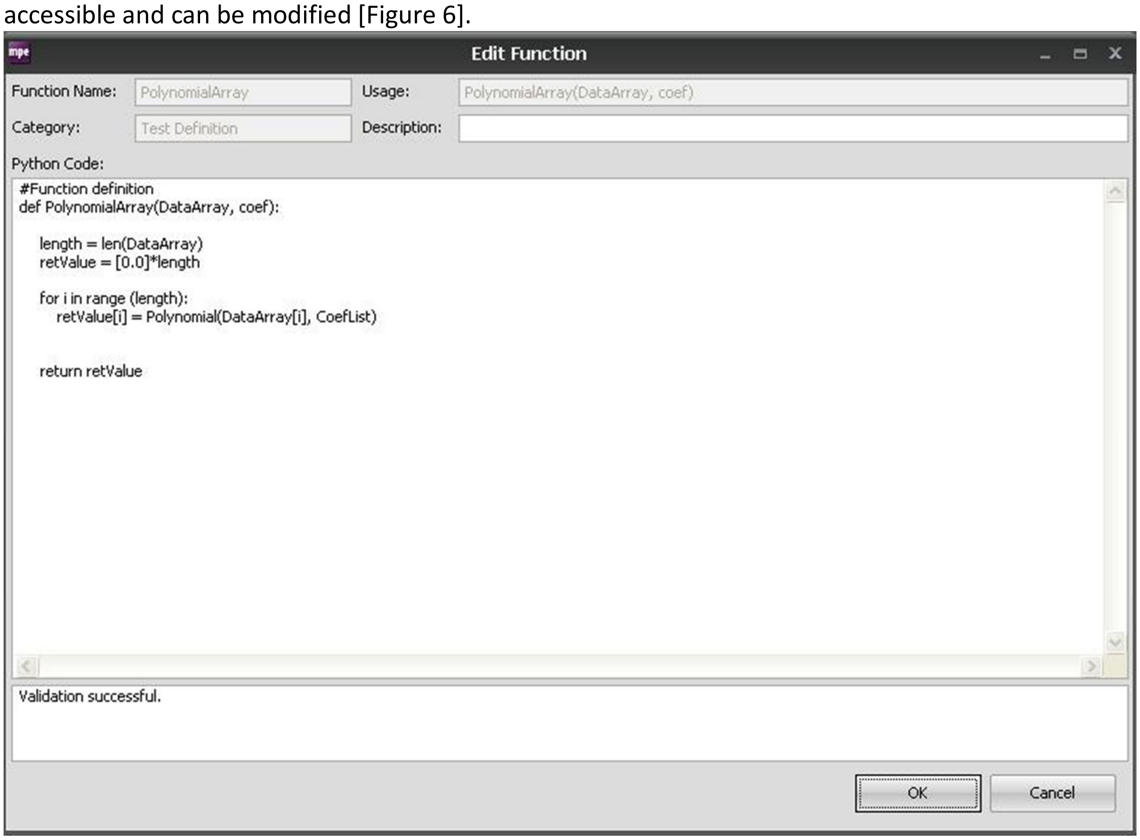


Figure 6: Function editor with Python Language

3. Test Execution

3.1 Monitor View

It is useful to plot simultaneously during the test the temperature and strain versus time. The monitor view can be adjusted by the user to select different channels, tests parameters, curves, etc. while the test is running [Figure7].

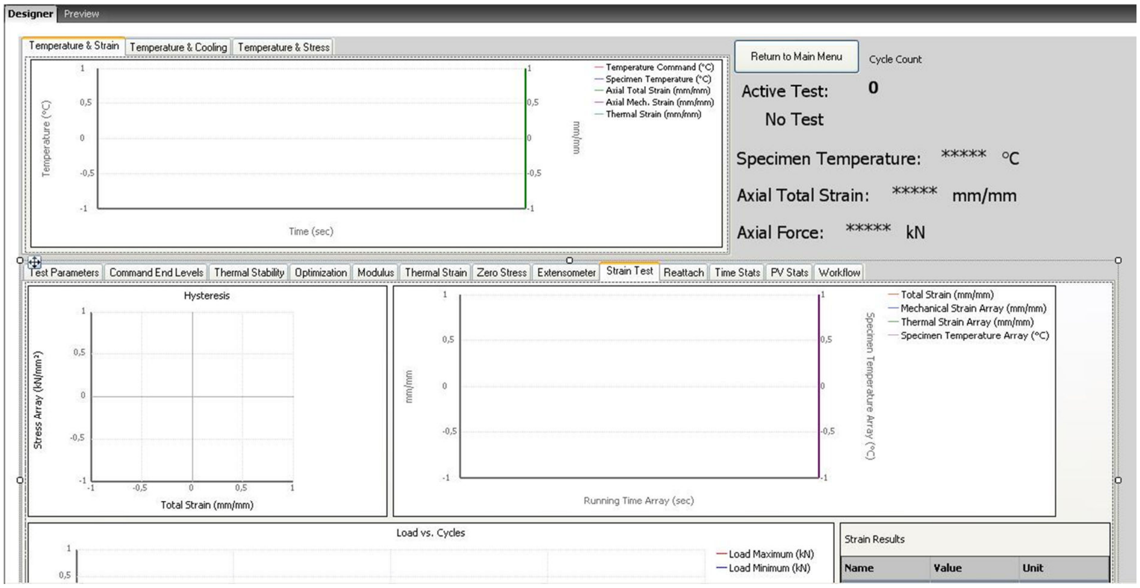


Figure 7: Monitor View to display the temperature
and strain vs. time

This is accomplished with a tool box [Figure 8] which gives access to all information such as scopes, counters, data tables, etc..

There is also the possibility to see the workflow. This display detects when and where an activity stops.

By incorporating tabs it is also possible to define display items that belong together and display them in their own tab.

Figure 8: Tool box showing the different elements to create

3.2 Reporting

The code of practice defines the information which needs to be reported. This information includes specimen, equipment details, test method, failure criterion, measurement error and other results. Once again, flexibility is needed. To do this, MTS a developed a specific tool, called an Excel Add-In, which is a new tool bar under Excel and allows various data to be reported. This includes variable values, tabulated data and charts, including elements from the run time display [figure 9].

A fatigue analyzer tool is also available, which gives the ability to plot the stress vs. strain for a number of cycles and then perform graphical analysis such as displaying a data drop range. This specific tool is out of scope of this paper.

STRAIN TEST REPORT

MERNo	MERNo	Test Machine	Test Machine
Test Type	Test Type	ServoController	ServoController
Specimen Number	Specimen Number	Heating Type	Heating Type
Project	Project	Heating Manufacturer	Heating Manufacturer
Material	Material	Heating Controller	Heating Controller
Date Of Test	Date Of Test	Feedback Type	Feedback Type
Tested By	Tested By	Extensometer	Extensometer
Comment 1	Comment 1	Software	Software
Comment 2	Comment 2	Template Version	Template Version

Specimen Description

Specimen Name	Specimen Name
Geometry Type	Geometry Type
Diameter (D)	Diameter (D)
Area	Area
Extensometer Gage Length (L)	Extensometer Gage Length (L)
Elastic Modulus (E)	Elastic Modulus (E)

Figure 9: Partial View of a Generated Report Created by the Excel Add In

4. Results

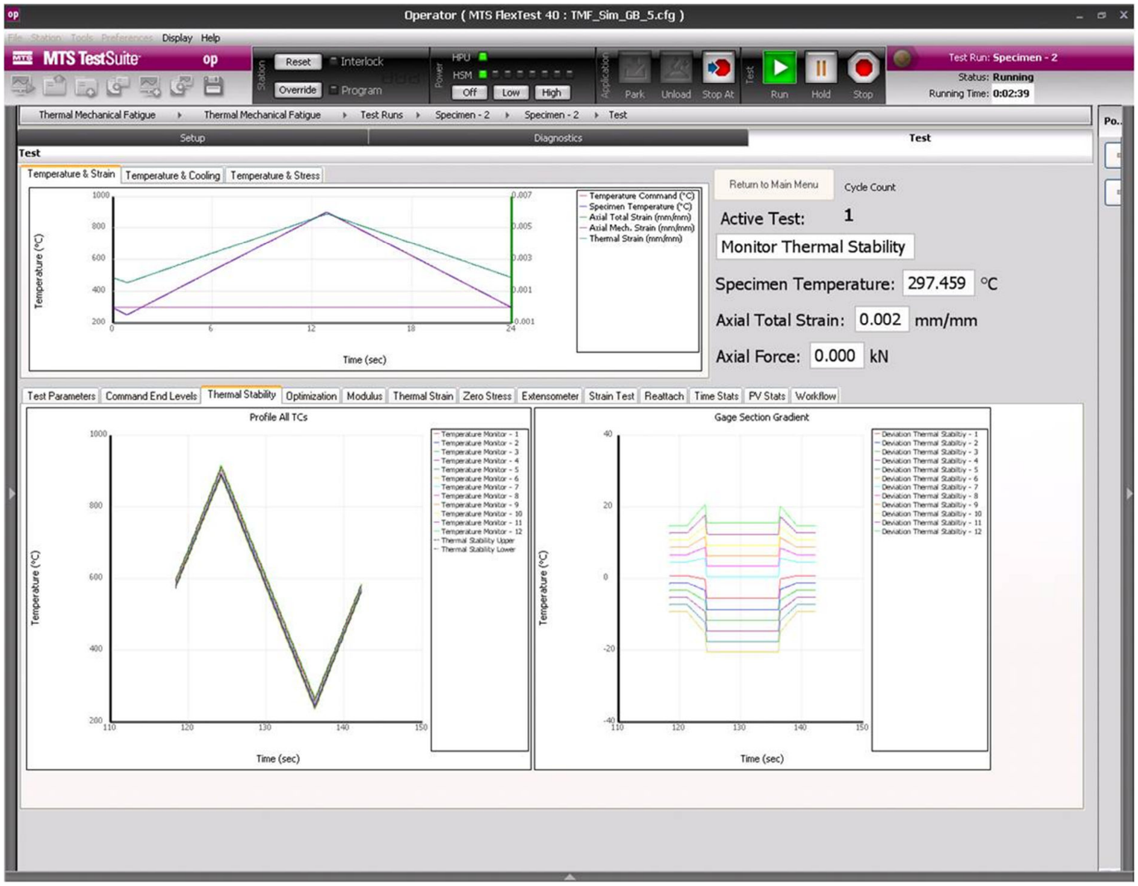


Figure 10: Thermal Stability Review

Figure 10 shows the three graphs which have been selected in the temperature and strain portion of the run time display.

We can see the thermal ramps applied. This graphs show that the mechanical strain stays flat when the temperature command and the achieved specimen temperature perfectly overlap. The upper curve corresponds to the total strain which is the sum of the mechanical strain and the thermal strain.

At the bottom left the temperature monitoring shows the thermal stability and at the bottom right the thermocouple readings indicated the temperature gradients. This display validates the fact that the desired temperature gradients have been achieved.

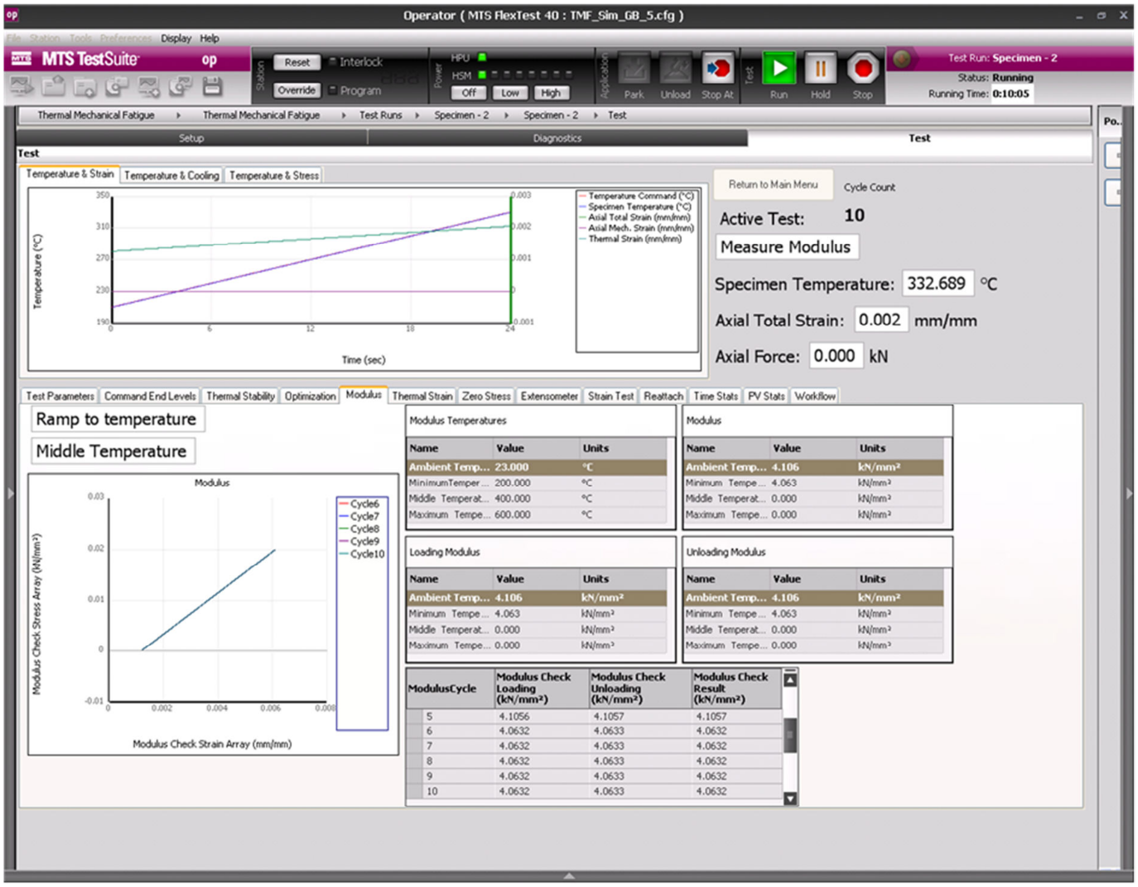


Figure 11: Modulus Check

Figure 11 shows the modulus tab. It superimposes five different cyclic ramps and gives the loading and unloading modulus for each cycle. It confirms the material constants for these different regimes between 200 and 600 °C.

On the next figure [Figure 12] we see the strain test. This main part of the test will cycle the material in strain control until failure occurs. The figure below shows the state after 5 cycles, with all parameters in a nominal state.

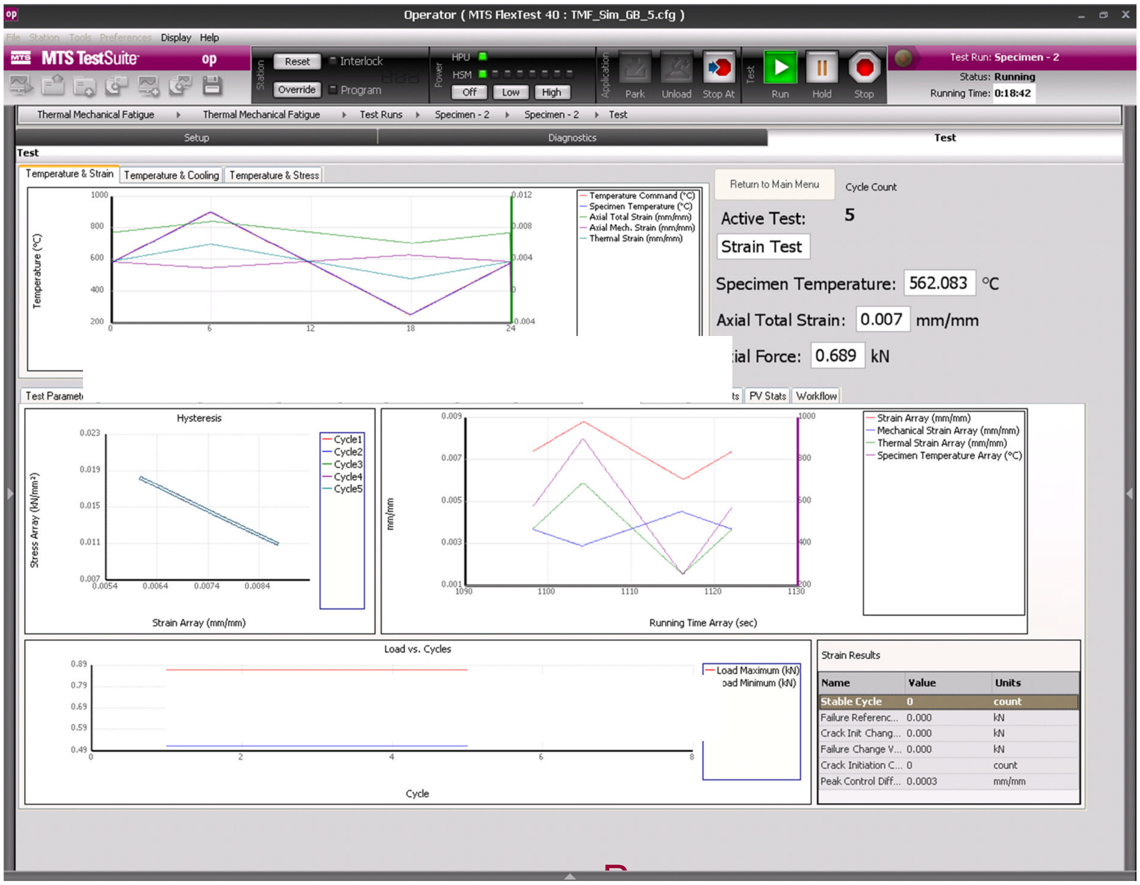


Figure 12: Strain Test

5. Conclusion

The new generation of software allows setting up complex procedures such as thermo mechanical fatigue tests. Different levels of controls are possible, from standard channel plotting to complex function settings, through the use of the open source Python programming language, embedded in the MTS TestSuite platform.

This opens up the possibility of nearly unlimited flexibility in terms of algorithm implementation, feedback controls, and analysis and reporting. It gives also the flexibility to adjust and customize any specific template depending on the test and or the user. This platform allows focusing on any detailed part of the test allowing for a better understanding of the material behavior.

6. References

[1] Special applications of standard software on to extend the capabilities of modern digital controllers.
E.A.Schwarzkopf, D.C Salmon MTS Systems Corp USA
Associazione Italiana per l'analisi delle sollecitazioni XXXIV Convegno Nazionale Politecnico di Milano

[2]EUR22281 EN DG JRC Institute for Energy
Validated code of practice for strain controlled thermo mechanical fatigue testing
P.Hahner European commission NL-1755 ZG Petten
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T.Beck Univ Karlsruhe Institute fur Werkstoffkunde I, D-76128 Karlsruhe
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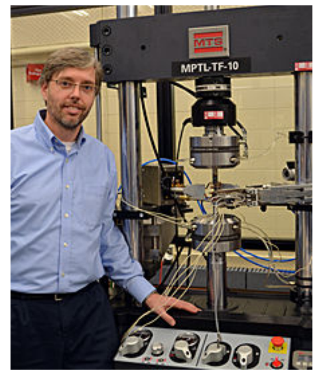
IN THIS ISSUE

Up To Code

Dr. Christoph Leser is the product manager for materials testing software at MTS. He has nearly 20 years of experience as a researcher, test engineer, application engineer and test consultant, and is a subcommittee chairperson for ASTM. Here, Dr. Leser describes how materials researchers can achieve consistent results in thermomechanical fatigue (TMF) testing with greater confidence.



Dr. Leser with thermomechanical fatigue test setup


Monitoring thermal gradients in preparation for thermomechanical fatigue testing

Q: What factors contribute to the rising importance of TMF testing in materials research and development?

Leser: Two of the most exciting areas in materials R&D today are related to the turbines used in aerospace and power generation. In both cases, designers are pushing operational efficiency and reliability beyond all previous expectations. To do that, they need turbine components and structures that can withstand higher temperatures for longer periods of time under a variety of cyclic loading conditions. Materials under investigation include innovative superalloys, ceramic matrix composites, ceramic coatings and others. Knowing how these materials react to simultaneous changes in temperature and load make TMF an essential part of the R&D process.

Q: Can you describe the mechanics and objectives of TMF testing?

Leser: TMF testing is a kind of fatigue testing that simulates the real-world service conditions of engineered components as closely as possible. Specifically, TMF tests characterize the response of materials to simultaneous cyclic mechanical loading and fluctuating temperature, which produce a synergistic response that is not easy to predict using isothermal fatigue testing. The data generated through TMF testing helps researchers model component behavior as well as validate existing models in a controlled test environment.

Q: What are the unique challenges of TMF testing?

Leser: TMF can be difficult because it uses in-phase and out-of-phase mechanical and thermal cycling. The phase shift between temperature-induced and mechanically induced strain invites numerous interpretations of material behavior. You need to apply heat using radiant or induction methods, which may require cooling. Test equipment and fixturing must be able to withstand high temperatures. Capturing accurate data is hard because high-precision systems behave differently at very high temperatures. The type of material being tested influences each setup, and there are many options for instrumentation, heating, cooling and fixturing. For all of these reasons, TMF testing tends to be customized and complex.

Q: Given this complexity, how can researchers hope to achieve consistency from test to test and lab to lab?

Leser: There are standards from ISO and ASTM researchers can follow, which provide best practices for consistently characterizing materials subjected to simultaneous thermal and mechanical loads. The TMF Code of Practice, which was created by a consortium of international partners, is another recent example. As I mentioned, one of the big challenges with TMF is that total strain includes thermal and mechanical components, and you have to know the precise distribution. For this reason, the TMF Code of Practice reduces the phase shift command to two possibilities: in-phase (maximum strain at maximum temperature) and out-of-phase (maximum strain at minimum temperature) cycling. The code also includes all the steps required to perform the test, from calibration to data reporting.

Q: How can researchers be confident they are meeting the requirements in the TMF Code of Practice?

Leser: Researchers can adhere to the code — and address the complexity of TMF testing — using advanced software solutions. MTS, for example, created a TMF template for MTS TestSuite™ Multipurpose software. The template is compliant with both ASTM standards and the TMF Code of Practice. It is completely transparent, providing full insight into its algorithms and calculations. You can use it to interpret standards in different ways, and you can modify the template for your own needs to gain new insight. All of this allows researchers to perform many different TMF tests for a diverse array of materials and specimen geometries.

Q: What features of the template and the software are particularly suited to TMF testing?

Leser: The template gives researchers explicit access to the activities required to perform the test through an intuitive graphical interface. Each task from the TMF Code of Practice is represented in the template by a button from the command panel, and each button is defined by a program block the user can modify. Basically, if you can see it, you can change it. This applies to test calculations and workflow, as well as the visual representation of data during the test, which offers unlimited views and is user-configurable. It also applies to results, so you can export the data and present results in the format that works best for your needs.

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