MTS – TRUMPF Collaboration on Multiphysics Simulation of Grip and Heating Coil in Support of a Thermomechanical Fatigue Testing Solution with Induction Heating

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1. Introduction

Presented herein are the results of a simulation study for a mechanical gripping and inductive heating solution to test small specimen under combined fatigue loading due to mechanical deformation and superimposed temperature influence.

Increasing demand for small specimen testing at high temperatures is driven by Additive Manufacturing applications and the evolving standards to validate predictions for and ensure quality of additive manufactured materials and components.

For more than 10 years, MTS and TRUMPF have worked together to develop heating solutions for advanced materials tests requiring the combination of mechanical and temperature influences. This type of testing is commonly called Thermo Mechanical Fatigue testing, TMF.

MTS and TRUMPF have performed a modeling study with detailed CAD geometries of specimens, grips, and heating coils. Multiphysics models give a high level of confidence in predicting the ability to achieve the required temperature, heating rates, and temperature distribution across the length of the specimen test (gage) section.

For this particular study of a small specimen at relatively high testing force, MTS and TRUMPF envisioned a new grip design which necessitated a new design for a heating coil as well. Requirements were set for achieved maximum temperature, the heating and cooling rates, and the homogeneity of the temperature distribution across the test section. Further, there were requirements for attaching a contacting extensometer, and also providing visual access to the specimen for potentially using a non-contacting, optical, extensometer.

The proposed solution consisted of a mechanical grip rated at 5 kN in fully reversed fatigue loading and an open fork style induction coil.

2. Grips

MTS has already developed grips for small specimen testing with 2.2 kN static and 1.1 kN dynamic load capacity for tensile and fully reversed fatigue applications respectively.

A patent has been granted to MTS for this grip set due to its unique design features for mounting a specimen within the grip and mounting of the grip via a “jig” to a load frame.

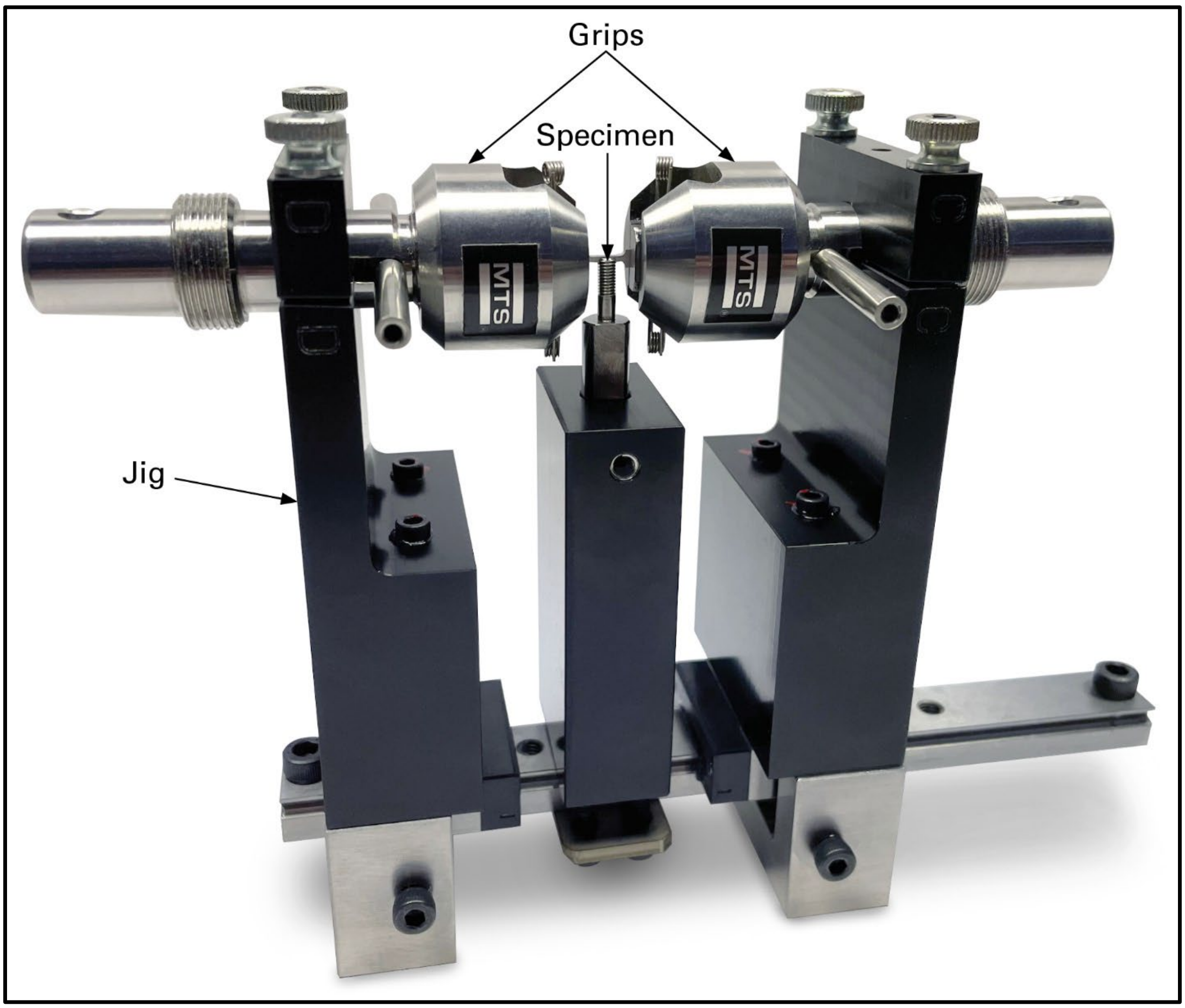

Figure 1: Mini Grips and supporting “Jig”

The mounting jig allows the insertion of the specimen into the grip outside of the load frame, e.g. on a work bench. This allows for optimal access to the grip and easiest handling of the specimen. The jig is designed in a manner that when the specimen is placed in the jig and the grips clamped to it, that the specimen alignment will be repeatable. The jig also bridges extraneous loads and prevents any loading of the specimen prior to testing it. The entire jig is then inserted into the load frame while an initial zero-load control command is issued. The jig gets removed and the test can start.

This grip is made of stainless steel and while rated for room temperature could be used in environments up to 315 °C.

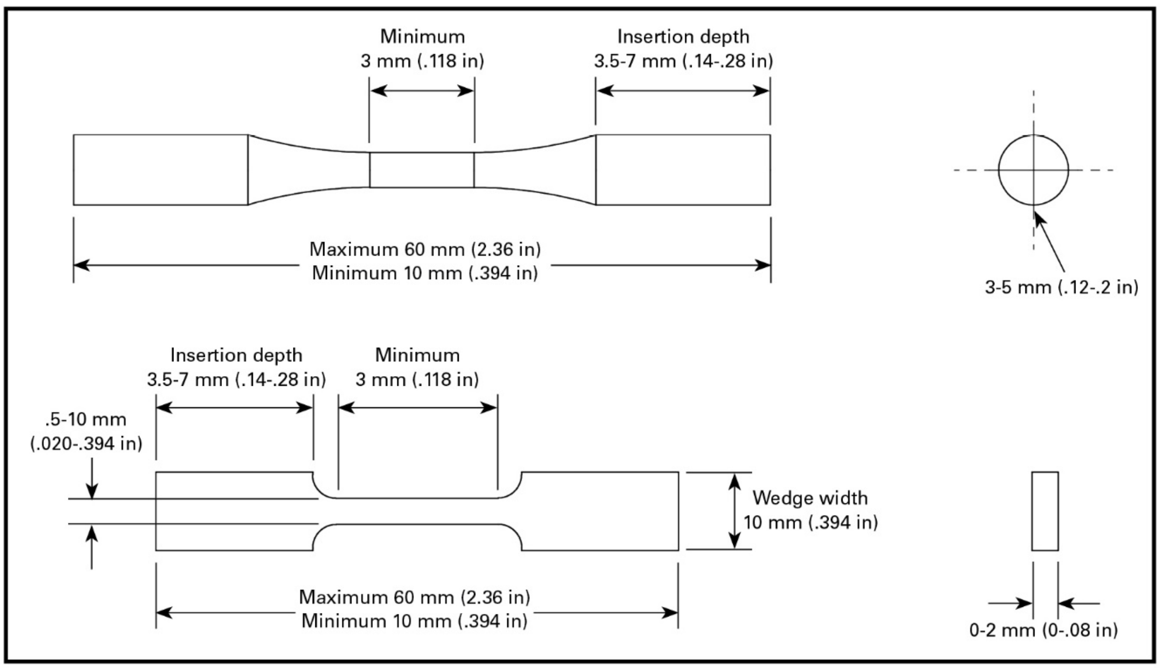

Figure 2: Mini Grip and supported specimen sizes

A new grip of similar design with an expanded geometric/performance envelope has now been considered. This grip is to provide the capacity to test up to 5 kN dynamic load under fully reversed conditions, while simultaneously allowing heating such that a maximum temperature in the testing zone of 900 °C can be achieved.

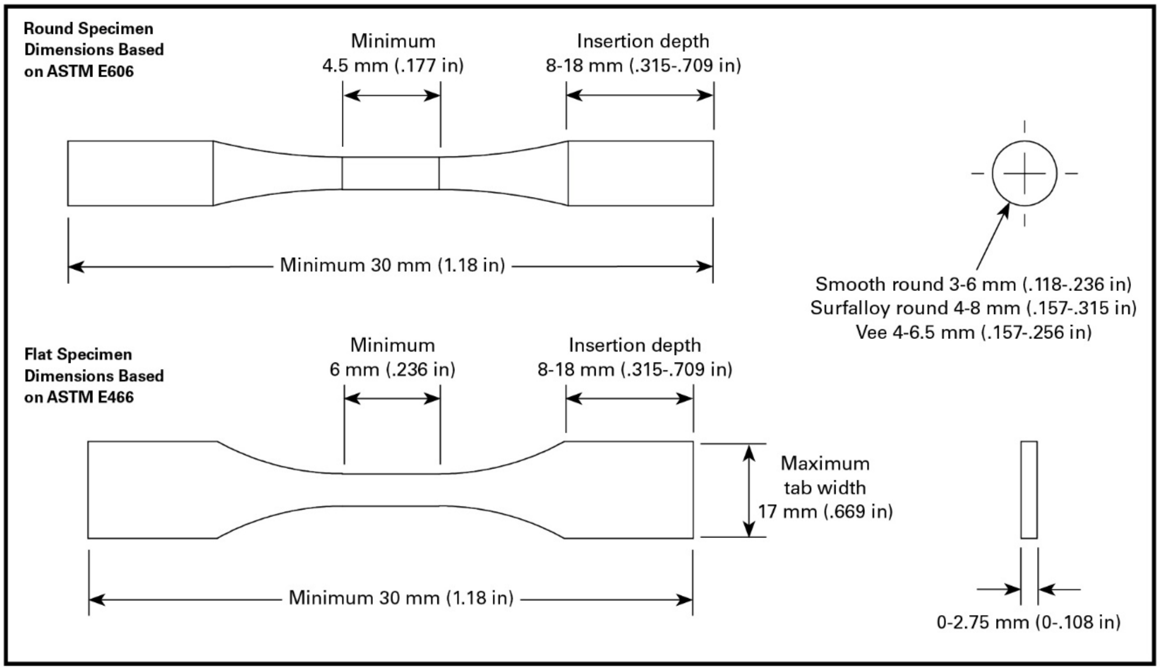

Figure 3: Expanded performance Mini Grip and supported specimen sizes

The specific geometry and load case investigated in this study are a flat specimen with a total length of 32 mm, a width in the gage section of 2 mm, a width in the end sections of 6 mm, a gage length of 8 mm, and an overall thickness of 1 mm.

The maximum load applied in fully reversed fatigue is 5 kN and temperatures range from room temperature to 900 °C.

This performance envelope is expected to meet emerging testing standards for small specimen testing. The material chosen by MTS for the grip to optimally support these requirements from a load and temperature carrying capacity is Udimet.

3. Heating Sub System

An inductive heating system is used to generate temperatures within the specimen. Due to the nature of inductive heating, rapid increases and decreases in temperature can be achieved, with typical ramp rates of 30 Kelvin per second or faster. A hollow copper tube with rectangular cross section is wrapped around the specimen and is energized with up to 1400 V, currents of up to 560 A and an excitation frequency in the range of 50-800 kHz.

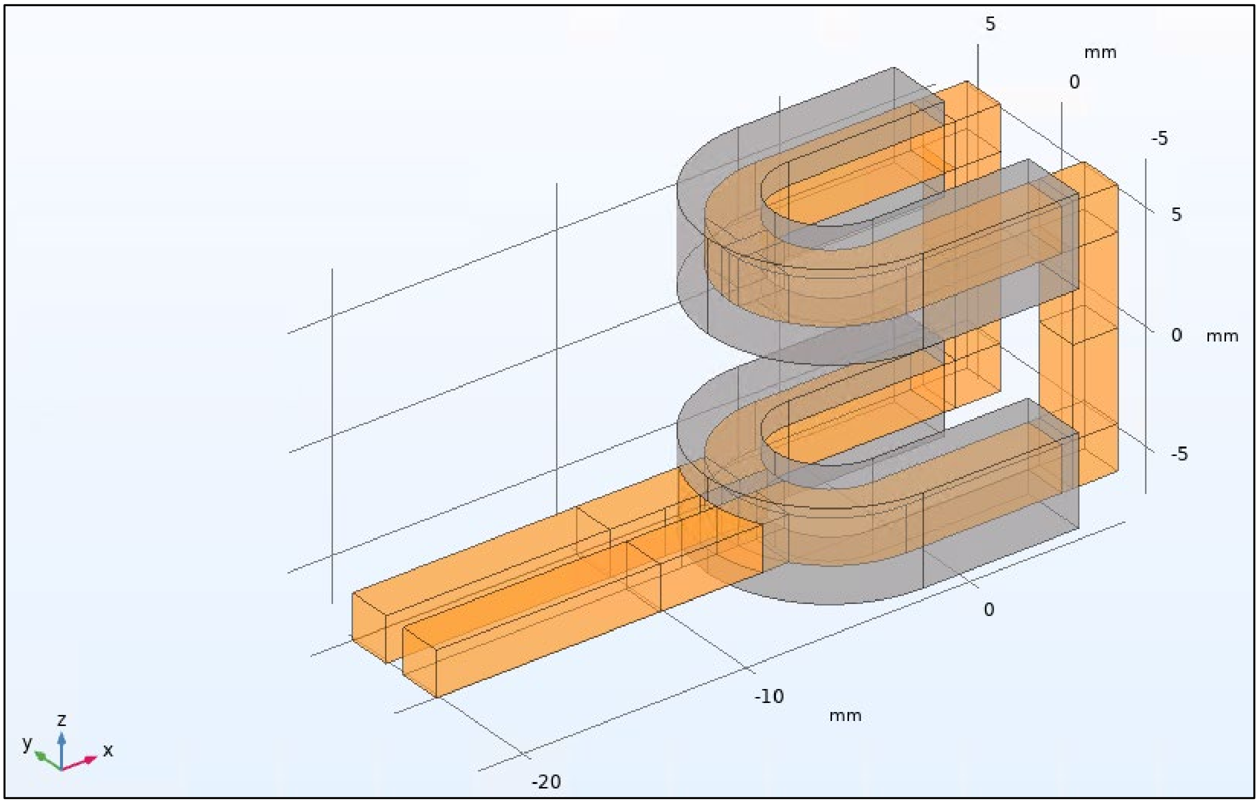

Figure 4: Proposed heating coil geometry

4. Heating Simulation

Due to the complexities of small specimen geometry, simultaneous load and temperature application and the need to find an optimal grip and heating coil design that depend on each other, a simulation approach was chosen for this multivariate optimization problem. All calculations and illustrations below assume a specimen that is symmetric around the center line of the middle of the gage length.

The coil design (Figure 4) was tailored to address the following challenges:

- Accessibility at specimen for measuring equipment (thermocouple, extensometer)
- Available space for induction coil between grips (Figure 5)
- Dimension of the coil with minimum diameter that allows internal water cooling
- Heating rate at specimen and associated induced power level dependent on current and excitation frequency
- Homogenous temperature distribution across the test section while accommodating heat sinks at the specimen ends due to the grips, i.e. goal to minimize the temperature deviation across the specimen gage length, Delta T
- Temperature control across the entire temperature range

- Change of specimen material properties during heating, with the Curie temperature of ferromagnetic steel being the most critical

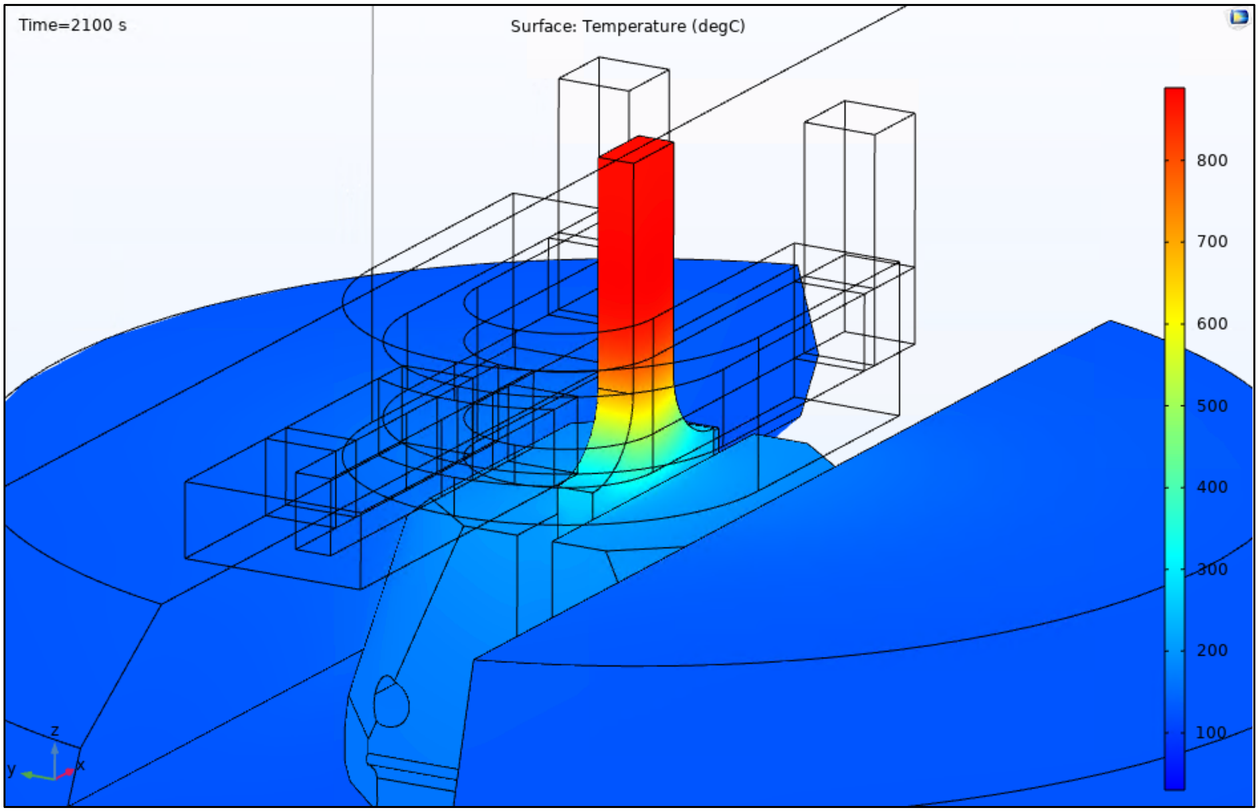

Figure 5: Temperature distribution after rapid heating with 30 K/s from 300 °C up to 900 °C

Specific requirements for the heating application were:

- Maximum achievable temperature: 900 °C
- Ramp rates for heating and cooling: 30 K/s
- Uniform temperature distribution across the gage length: within 10 K

An initial grip design was undertaken and analyzed via FEM methods for fit and function with respect to geometry, strength, stiffness and durability.

An induction coil was laid out to allow for uniform heating of the specimen. There was physical access to the specimen to attach a strain-gage based extensometer, and visual access to the specimen for a non-contacting extensometer. A thermocouple mounted on the specimen allowed for temperature control.

A multiphysics simulation using COMSOL Multiphysics software was undertaken. This approach is characterized by:

- Ability to deploy 2D and 3D simulations depending on the geometry of specimen and coil
- The electromagnetic field of the induction coil is typically simulated as a frequency domain problem
- The thermal field inside the specimen can be simulated either as stationary or transient
- Thermal and magnetic fields can be coupled via temperature dependent material properties such as electrical conductivity, relative permeability, thermal conductivity, specific heat capacity
- Consideration of heat transfer via radiation, convection, and conduction
- Consideration of end effects due to gripping of specimen ends that attach to potentially water-cooled grips

The main parameters considered for the optimal coil design are:

- Excitation frequency 400 kHz
- Coil current level up to 460 A (rms)
- Temperature dependent specimen material properties of steel alloy Inconel 718
- Temperature of cooling water inside grip cooling channels of 30 °C
- Thermal contact model of COSMOL between specimen and grips
- Surface-to-ambient-radiation at the diffuse surface of specimen
- Magnetic and thermal fields are bi-directionally coupled

Final design iteration and conclusions

- Fork-like coil with open front meets most heating and all accessibility requirements
- Heating rates up to 30 K/s (Figure 6)
- Temperature uniformity is less optimal than for a closed/surrounding coil
    - Achieved Delta T across the gage length was 14.8 K (Figure 7)
    - Further potential for better uniformity via additional coil design iterations is given
- Cooling rates (without active air cooling considered) strongly dependent on temperature values at grips (currently no grip cooling considered, “warm” grip)
- Standard TRUMPF generator with 10 kW is suitable
- Additional simulations prior to final coil design recommended
- Achieved temperature: up to 900 °C

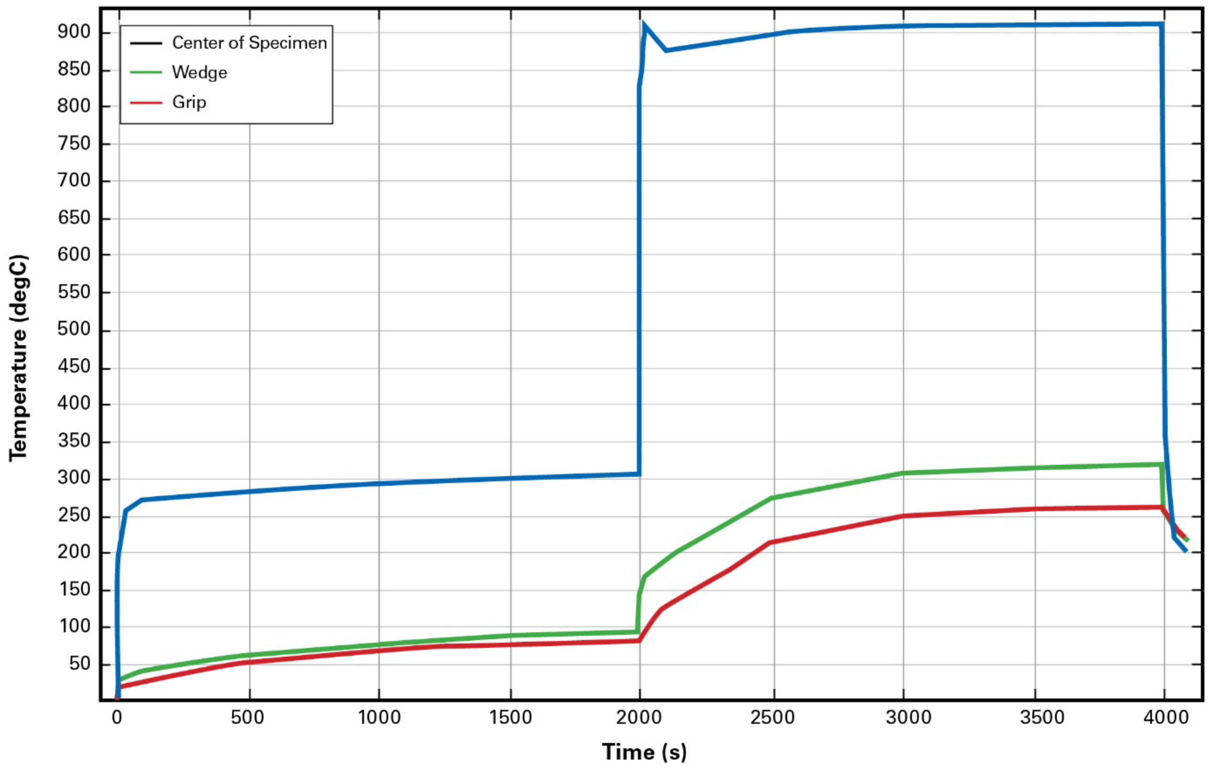

Figure 6: Temperature vs. time for a special heating procedure at different positions

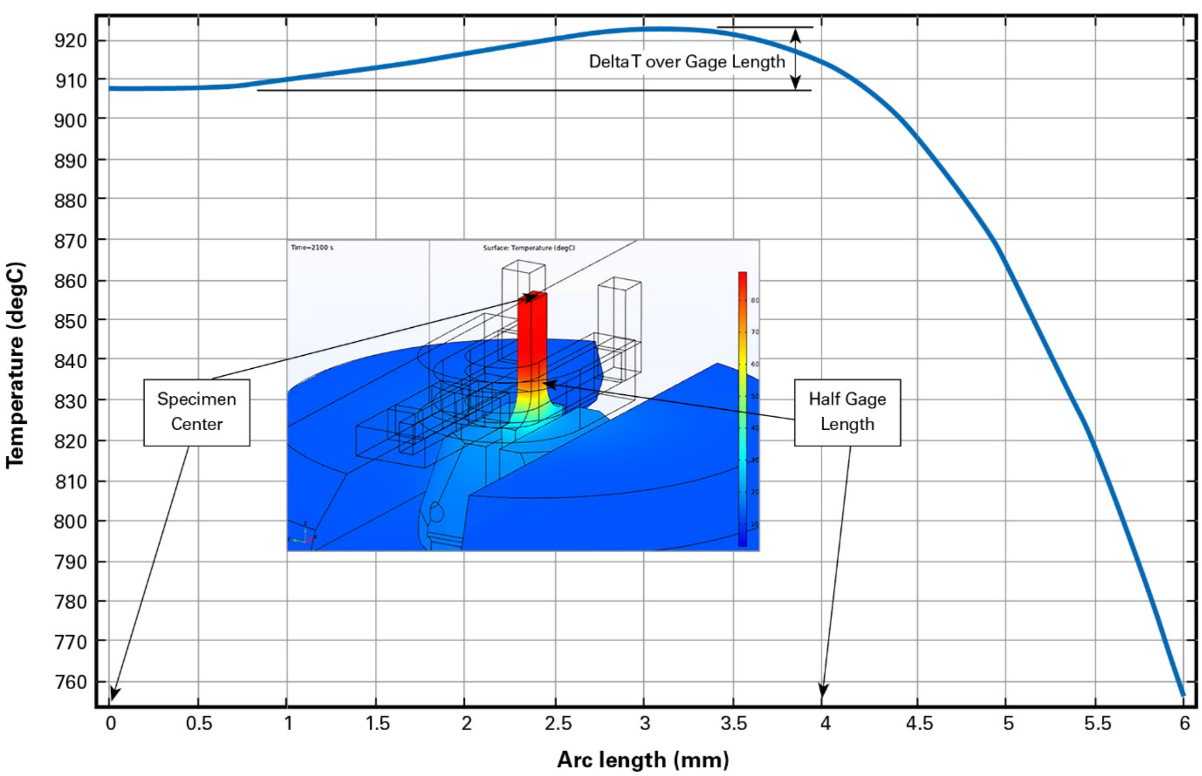

Figure 7: Temperature along specimen at steady state after a soak time of 1500 seconds. Delta T = 14.8 K, Center position at 0 mm, Gage length 8 mm.

5. Summary

The learnings from this study allow MTS and TRUMPF to mitigate against the risk of not meeting requirements by offering simulation studies prior to building actual hardware.

Requirements for the application were largely met with the iterated design, with some compromise on achieved temperature distribution in the maximum temperature condition.

However, there remains uncertainty in the modeling due to factors that were not considered, which are, among others:

- Attachment of the extensometer to the specimen
- Final material properties of the specimens under test
- Geometric tolerances of the specimen

Therefore, MTS and TRUMPF deem this approach a good first step to specifically evaluate required performance for a given design prior to building any prototypes. The simulation is a suitable low cost early step to determine overall performance of a specific design and, as a model-based approach to design, it helps identify areas of risk and gives guidance for improvement. A final validation via a physical prototype is recommended before signing off on multiple builds of any specific design.