Thermal analysis and experimental testing of clamping jaws for thermomechanical simulator

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Abstract. This paper presents a thermal analysis of clamping jaws for a thermomechanical simulator, which is compared with the results from a thermal camera and thermocouples placed directly on the specimens during experimental testing. The clamping jaws have several cooling circuits inside of them and are actively cooled throughout the process. The test specimens are in turn heated by high-frequency electrical resistance heating. During the testing, it was observed whether the cooling system is sufficient, partly because polymeric materials are also used on the jaws to electrically insulate the system. Based on the measurements, it was found that even though the test specimen is heated almost to 1000 °C for a long time, the temperature of the jaws does not exceed 40 °C. The suitability of the proposed cooling system was proved and also the satisfactory agreement of experimental measurements with numerical simulations was achieved.

Keywords. thermomechanical simulator, thermal analysis, thermal camera, heat treatment, clamping jaws.

1. Introduction

The development and optimization of a heat treatment and mechanical working of forged parts would be very time-consuming and costly if carried out right in the production line. For this reason, a thermomechanical simulator has been developed. Using the simulator, mechanical loads, as well as loads from forces, deformation and heat acting on a real-life product during various manufacturing processes can be simulated. The paper [1] describes this testing system and the related methodology. The agreement between the characteristics of a real-life product and the data from the simulator is demonstrated using an example of a closed-die forging. The comparison involved mechanical properties and microstructures. Results achieved on numerous other products, such as sheet metal, rods, wires and others, prove that material-technological modelling with the aid of this newly-developed equipment is a cost-effective method of modelling real-life manufacturing processes in laboratory conditions [1].

The aim of this paper is to validate the specimen temperature during the process and also to validate the jaws cooling system. Papers [2-5] are examples of practical use of a thermomechanical simulator.

2. The thermomechanical simulator

The thermomechanical simulator serves to simulate and optimize the processes of thermal and mechanical processing of forgings and other steel components. Using a thermomechanical simulator, it
is possible to simulate, for example, forging, quenching, tempering and other mechanical, force or deformation and temperature loads of test samples.

The simulator of thermomechanical processes is under long-term development at the departments of the Research Centre based at University of West Bohemia in Pilsen. Its primary purpose is laboratory-based simulation and optimization of real-world processes used in thermomechanical treatment of metals in industry [1].

The simulator consists of three subsystems. Its core is the MTS FlexTestSE electro-hydraulic testing system with clamping jaws [1]. The second subsystem is a specimen heating system. It relies on high-frequency electrical resistance heating. At its core there is a multi-stage controller as a single-chip computer and FPGA with a patented power converter control method [6]. Specimens can be heated in a controlled manner at rates in excess of 200 °C/s, depending on the material and shape of the test piece. The third subsystem of the simulator is the cooling system. Like the others, it is a feedback-based unit linked to the heating system. The maximum available controlled cooling rates are up to 100 °C/s [1]. More about thermomechanical simulator was presented in papers [1]. Figure 1 shows the entire thermomechanical simulator and the detail of the clamping jaw with the clamped specimen. Examples of clamped samples are shown in Figure 2.

Development process and description of the resulting design of the new generation of clamping jaws for thermomechanical simulator is given in the publication [7].

![Figure 1. Current solution of thermomechanical simulator.](image1)

![Figure 2. Examples of clamped specimens, a) cylindrical, b) sheet-metalical.](image2)
The upper and lower jaws are each divided into a fixed and a removable part. In all these 4 parts, separate independent cooling circuits are created, which are shown in figure 3.

![Diagram](image)

**Figure 3.** Sectional view through the cooling system.

3. **Experimental testing**

3.1. **Definition of specimens**
A cylindrical steel specimen, as shown in Figure 2 above, was chosen for experimental testing. The specimen has a diameter of 8 mm in the middle part and an M16 thread is created at both ends. The total length of the specimen is 100 mm, of which the middle measured part is 25 mm.

3.2. **Definition of boundary conditions**
The frequently used temperature characteristic was chosen, which is shown in Figure 4. This is the temperature in the middle of the sample. The indicated temperature is measured by a thermocouple throughout the process and regulated by a multi-stage controller in real time. Heating is provided by the above-mentioned high-frequency electrical resistance heating and cooling is provided by a series of nozzles using a combination of water and air.

![Graph](image)

**Figure 4.** Temperature characteristic used for experimental testing.

The jaws are continuously cooled throughout the testing. Ordinary tap water is used. At the time of the experiment, the water temperature was 21 °C. According to the legislation [10] (ČSN EN 806-2: 2005), the temperature of the cold tap water must not exceed 25 °C. It can therefore be expected that the coolant temperature will always be at most 25 °C. The ambient temperature was 24 °C and the relative humidity in the laboratory was 52 %.
3.3. Monitored parameters
During the experimental testing, the temperature of the specimen and the temperature of the jaws on their side and on the forehead were monitored by a thermal imager. Images were taken at times $t = 0$, 250, 450 and 1000 s.

Since the used thermal camera’s (MICRO-EPSILON / TIM 400) ranges for measuring are 0 to 275 °C and 150 to 1250 °C, at time $t = 200$ s an image was taken in both ranges in order to determine the correct temperature of the specimen and jaws.

3.4. Thermal-camera outputs
At time $t = 0$ s (i.e., the initial state before heating the specimen), the state was such that the measured temperature of the specimen was 24.5 °C and the temperature of the side of the jaws was 25.2 °C. A temperature of 30.2 °C was measured at the front of the jaws, however, it should be emphasized here that this area was measured at a greater angle and it is also the area that pointed towards the laboratory windows. The image from the thermal imager is shown in figure 5.

![Figure 5. Image from thermal camera at time $t = 0$ s.](image)

Figure 6 shows an image from a thermal camera at time $t = 250$ s, which had to be composed of two images taken immediately one after another. In the image we can observe that the temperature of the centre of the specimen increased to 953.1 °C, yet there was only a slight increase in the temperature of the jaws themselves, i.e. by 1.2 °C on the side and 1.9 °C on the front of the jaws.
Figure 6. Image from thermal camera at time $t = 200$ s.

Figure 7a) shows the image at time $t = 450$ s, when there was a very rapid cooling from high temperature and subsequent equalization to a temperature of 210 °C according to the thermocouple, respectively 208.1 °C according to the thermal camera. The jaw temperature increased to 28.9 °C and 31.2 °C. At a time of 1,000 s, when the temperature of the specimen was stabilized at 210 °C for 550 s, there was a slight decrease in the temperature of the jaws to 26.9 °C and 31.1 °C. According to the thermal camera in figure 7b), the temperature of the specimen is only 195.5 °C, although the thermocouple indicates exactly 210 °C, but this may be due to dross formed on the specimen surface and having a different emissivity than the specimen itself. However, the temperature of the jaws is not affected by this inaccuracy, because of course no dross is formed here.

Figure 7. Image from thermal camera at time a) $t = 450$ s, b) $t = 1,000$ s.
4. Thermal simulation

The required temperature of holding jaws is under 40 °C. The required capacity of cooling system was simulated. The thermal simulation was launched in the simulation software Siemens NX12. A basic level of thermal simulation is represented by the Nastran solver. It is able to solve thermal fields, thermal transfer between parts and convection. Solved convection is based on thermal transfer coefficients [8]. An accuracy of thermal transfer simulation is highly dependent on predefined thermal transfer coefficients. A steady state simulation and a transient solution are defined.

The real test duration is 1,200 seconds, transient solution is solved in this time schedule. The cooling liquid in the cooling circuit is pure water. Input thermal loads are defined by heat loading of real test rig. Real thermal load is mode-rated by the isothermal function of specimen. It means, that heat load is general curve dependent on time. It is able in the Figure 6. Input fluid velocity is 0.5 m/s. Thermomechanical simulator uses compressed air and sprayed water to fast cooldown of specimen. Fast cooldown by sprayed mixture in time 300 s is simulated by fast increase of convection thermal transfer coefficient $4.5 \times 10^{-4}$ W/mm$^2$K. Model consists of 50K 3D elements and 11K 2D elements for surface coating. Ambient temperature and coolant temperature were set identical to the experiment. Results of simulation are in accordance with real test measurement and all results are shown in the table 1. An example of the simulation result is shown in figure 8. Requested temperature of jaw is under 40 °C. Time dependency of temperature of jaws can be seen in the figure 9b).

![Figure 8](image1.png)

**Figure 8.** Example from simulation at time $t = 250$ s.

![Figure 9](image2.png)

**Figure 9.** a) The course of the sample temperature and the heat load used to heat the specimen, b) the course of the temperature at the jaw surface.
5. Summary

Experimental testing and numerical simulation of the thermal process were performed using new jaws for a thermomechanical simulator. There are slight differences between the measured values and the values from the simulation, but the temperature trend is the same. When the sample is heated to 950 °C, the jaws are heated by less than 3 °C. After staying at a high temperature and rapid cooling, there is still a slight increase in the temperature of the jaws, however, while maintaining the temperature of the sample at 240 °C for a long time, there is a slight cooling of the jaws.

At the time of the experiment, the ambient temperature was 24 °C and the coolant temperature was 21 °C. Since it is possible to air-condition the room and the water temperature must not exceed 25 °C according to the legislation, we can state that the cooling system is sufficiently efficient.

It is important to remember that the heating reaches the pattern through the copper sheet and nut, which are in direct contact not only with the pattern but also with the jaws. The nuts in figure 8 were hidden so as not to cover the jaws.

A summary of the measured values and the values from the numerical simulation is given in table 1.

| Time [s]      | Experimental Testing | Numerical Simulation |
|---------------|-----------------------|----------------------|
| Centre of the specimen [°C] | 24.5 953.1 208.1 195.5 | 24.0 950.0 210.0 240.0 |
| Side of the jaw [°C]   | 25.2 26.4 28.9 26.9 | 24.0 26.5 28.2 27.3 |
| Forehead of the jaw [°C] | 30.2 32.1 31.2 31.1 | 24.0 28.1 28.5 28.3 |

6. Conclusion

Temperature effects on the jaws in which the high temperature specimen is clamped were investigated. The suitability of the proposed cooling system was verified by experiment and simulation. As the jaws are not very massive and a total of 4 cooling circuits are created in them, a very efficient cooling was achieved. The jaw temperature was required not to rise above 40 °C. In one of the longest tests monitored, the jaw temperature did not reach 35 °C at any time. The proposed cooling system can therefore be declared sufficient. The efficiency of the cooling system is positive especially because the insulation of the jaws includes polymer and silicone components that could be damaged by long-term exposure to high temperatures.

Technical solution of clamping jaws is protected as a utility model registered on The Industrial Property Office-Czech Republic [9].

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