Chapter 17
Modelling and Design of Systems for Active Control of Temperature Distribution in Frame Subassemblies

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Abstract This paper outlines theoretical and experimental investigations into opportunities for active control of heat flows in frame structures. The application of phase-change materials using metal foam as matrix material makes it possible to achieve an increased thermal capacity that is coupled with the frame structures as needed by means of variable thermal conductance based on active materials.

17.1 Introduction

The more inhomogeneous the occurring temperature fields, the more challenging it is to correct or compensate for thermally induced deformations, particularly if the frame structures do not reach a thermal equilibrium. In practice, the current desire for shut-down measures in order to increase power-efficiency results, however, in an increase in heat flows that are inhomogeneous both in time and location. To counteract the negative consequences of this phenomenon, an intervention must occur in the thermal effect chain at the level of the heat flow and the temperature fields that result from it. Influencing heat flows and temperature fields at the component level can thus enhance the thermal behaviour of the machine as a whole.

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17.2 Approach

Stabilisation given heat inputs that are inhomogeneous in time can be achieved by means of additional thermal capacities and a concomitant higher thermal inertia in the system. In view of this, a thermal equilibrium—once achieved—can be sustained longer against a varying heat flow. However, an increased thermal capacity has a disadvantageous influence on transient behaviour outside the steady state. Increased inertia can greatly delay or even prevent the achievement of thermal equilibrium (Fig. 17.1b). Possibilities for active control of heat flows were considered to improve this transient behaviour. In this process, a high-capacity heat storage structure is to be isolated from the component during warm-up. After the steady state is established, the thermal capacity is raised through thermal coupling with the storage and thus it is possible to input or output heat flows varying in time and/or amount in a controlled manner (Fig. 17.1c).

To implement the heat storage, phase-change materials (PCM) able to absorb or release large amounts of thermal energy within a small temperature range due to the enthalpy of thermodynamic changes of state were investigated. These materials provide high storage density in the range of phase transition (typically from solid to liquid), resulting in a thermal stabilisation in the range of the PCM's melting temperature. To optimise the thermal transfer inside or into the storage, the phase-change material was infiltrated into a substrate made of aluminium foam. Two material-based mechanisms were considered as a way to achieve variable coupling of the storage device to the component to be thermally regulated: first, the anisotropic behaviour of magneto-rheological fluids under the influence of the magnetic field, and, second, the mechanical response of thermal shape memory alloys to changes of the thermal field.

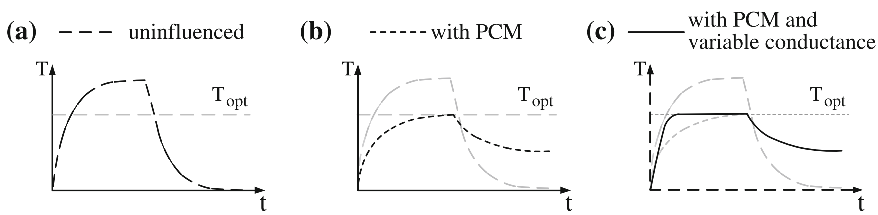

Fig. 17.1 Schematic view showing the influence of the considered measures **a** temperature curve, uninfluenced, **b** with heat storage, **c** with heat storage and variable conductance

17.3 Results

17.3.1 Material Composite of Phase-Change Material and Metal Foam

Closed-cell aluminium foam was considered as matrix for the phase-change material. Encapsulating the PCM in closed cavities ensures that the volumetric expansion in the phase transition (of up to 16 % in case of the PCM based on paraffin investigated here) does not affect the outside. The distribution of the PCM in small amounts in the composite material provides good heat introduction and thus makes it possible to absorb or release large heat flows. The infiltration of the foam takes place at temperatures above the paraffin's melting point after having evacuated the metal foam body or through dipping into a tank with liquid PCM. In this process, micro-cracks in the cell walls are used to enable the pores located inside to be filled (Fig. 17.2).

Fill rates of up to 100 % can be obtained with this technique. However, the actual fill rate depends on the statistical distribution of pores and micro-cracks. The volume of embedded PCM can be increased by a cooling down procedure during infiltration. The volume reduction during PCM solidification causes a partial vacuum, and additional material is drawn in. However, an increase in the fill rate due to this method is only desirable up to complete infiltration in the liquid state. If the cavities are completely filled with already partially solidified PCM, the volumetric expansion in the melting procedure will expand the PCM to a volume larger than the cavities, which is to be avoided.

Designing the matrix as a sandwich structure, in which the cover layers made of solid material are metallurgically bonded to the foamed core, is a measure to improve heat entry into the heat-storage structure. When metal foam structures are used in a sandwich design, two outer sides have already been sealed by means of the cover layers (see also Fig. 17.3). Additional sealing measures are necessary for the open outer sides that remain. In this context, sealing by forming proved to be an efficient method. Here, parts of the foamed core are removed and protruding cover sheet plates are bent and used for sealing. The bent cover sheet plates are either welded or glued.

A homogenized material model representing a substitute material, whose thermal behaviour conforms to that of the material composite, was developed. It is possible to determine the thermally relevant material properties of density ρ_h and specific

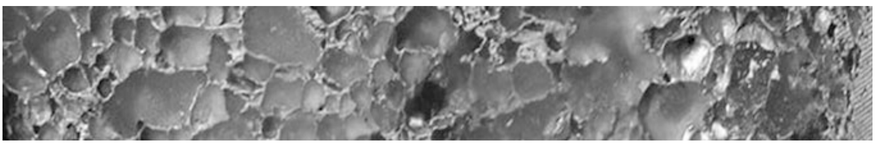

Fig. 17.2 Metal foam with PCM embedded in the pores

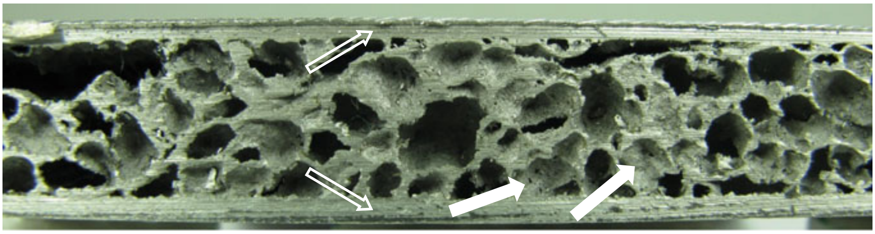

Fig. 17.3 Metal foam structure in sandwich design, micro-cracks in cell walls (*white arrows*), cover layers made of aluminium and metallurgically bonded (*white hollow arrows*)

thermal capacity $c_{p,h}$ for the homogenized material from the material characteristics of the aluminium- and PCM portions of the composite material by using (17.1) and (17.2).

$$c_{p,h} = \frac{m_{alu} \cdot c_{p,alu} + m_{pcm} \cdot c_{p,pcm}}{m_{alu} + m_{pcm}} \tag{17.1}$$

$$p_h = \frac{m_{alu} + m_{pcm}}{V_{ges}} \tag{17.2}$$

The influence of the latent heat that is absorbed in the phase transition can be represented by two approaches: first, by an increased specific thermal capacity in the melting region and, second, by specifying the temperature-dependent enthalpy. From a numerical point of view, the second approach is to be preferred, since the material characteristics do not change abruptly. Thermal conductivity of the metal foam can be determined using the modelling approaches by Singh and Kasana (2004), as well as Bhattacharya et al. (2002).

The two relevant variables—absorbable heat and thermal conductivity—conflict in terms of objectives. Thermal conductivity diminishes as a function of increasing porosity of the metal foam, on the one hand. On the other hand, the PCM volume that can be introduced, and, consequently, the absorbable heat, increase. As a result, it is necessary to weigh the respective importance of the variables based on the given requirements.

A basic demonstrator showed that the thermal behaviour of a plate structure can be influenced by infiltrating it with PCM. The basic body of 0.0013 m^3 volume and 786 kg/m^3 density was infiltrated with 0.49 kg PCM RT 33 by the firm Rubitherm and subjected to a heat flow of 19 W (Fig. 17.4 left). The influence of thermal stabilisation can also be demonstrated by simulation, by comparing metal foam elements with and without PCM (Fig. 17.4 right). Hence the results show the suitability of the approach and are generally in accord with the results previously published by Aggogeri et al. (2010).

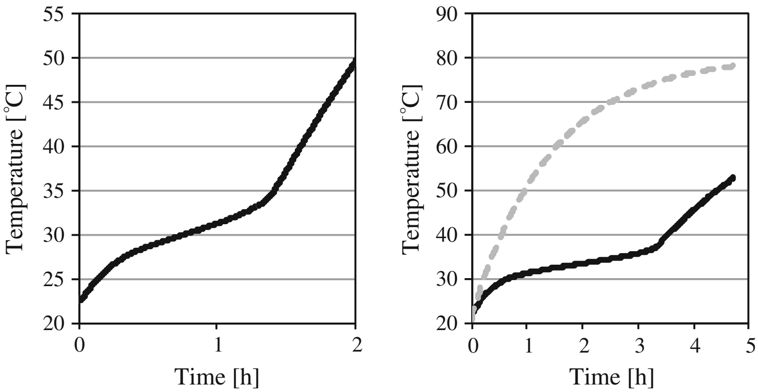

Fig. 17.4 Temperature curves obtained by experiment (*left*) and simulation for metal foam sandwiches with PCM (*dashed line* unfilled, *drawn through line* filled)

17.3.2 Switchable Thermal Conduction Based on Shape Memory Alloys

The working mechanism investigated to influence heat flows by means of thermally active shape memory alloys was to macroscopically influence the contact properties by opening and closing air gaps. Thermal shape memory alloys (SMA) can exert a force after reaching an activation temperature based on the one-way shape memory effect. SMAs exhibit a very large volume specific work capacity in comparison to other actuator-principles. This allows for a lightweight and highly integrated solution. Activation of SMA-actuators can be done actively by heating or by using the heat of the process itself.

Thermal equivalent networks are used to model the thermal conductivity properties. The thermal resistances in a contact are influenced by actuators based on shape memory alloys. Consideration of a simple heat transfer path in a beam structure, which can be influenced by actuators based on the shape memory effect, produced the networks depicted in Fig. 17.5. The heat bridge created in the experiment (Fig. 17.5a) consists of a heat source, a heat sink, and a structure with good thermal conductivity to connect sink and source. A v-shaped section of this structure can be inserted and pulled off via a shape memory actuator working against a spring. Thermal equivalent circuits for the setup are shown in Fig. 17.5b–d. In case of active triggering of the shape memory actuator, it was switched between arrangements with good and restricted heat transfer. In this setup, the shape memory actuator works against a resetting spring element made of conventional material. The latter opens up the transfer path in the basic state because the spring force of the resetting element exceeds the force of the actuator element. Due to heating of the active element, the force exerted increases beyond the reactive component, and the thermal contact is established. In experiments with

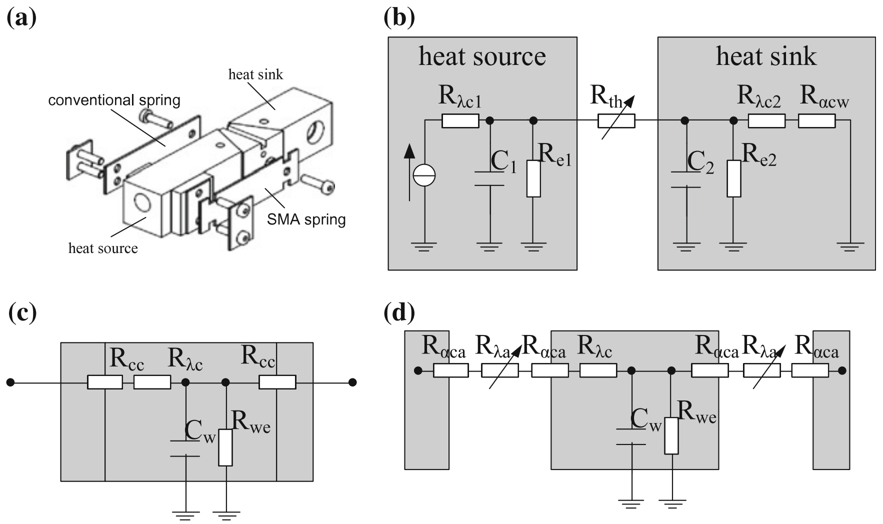

Fig. 17.5 Experimental setup of the heat bridge and thermal equivalent circuits. **a** Overview on overall setup. **b** Network of overall setup. **c** Network for closed heat bridge. **d** Network for opened heat bridge

the path open, heat source and heat sink differed in temperature by 80 K. Upon activation of the shape memory element, the gradient was reduced to 12 K. The resistance in this setup dropped from 16.2 K/W down to 2.3 K/W.

Actuators made of thermal shape memory alloys allow for a self-sufficient mode of operation due to the use of available thermal energy. By contacting an actuator element directly to the heat source, it is activated once a temperature threshold value has been exceeded. Figure 17.6 demonstrates the transient thermal behaviour of a setup like this: First, a high thermal load (30 W) was applied for 3,600 s. In the first case (heat source isolated from heat sink; “open gap”), this resulted in a rapid

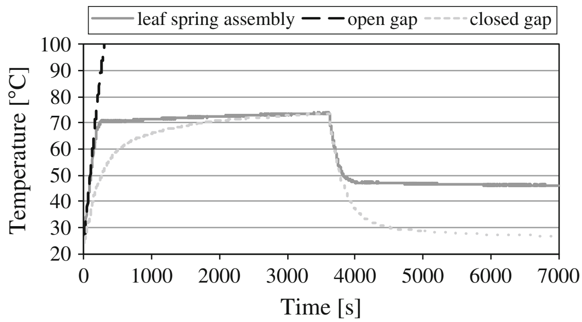

Fig. 17.6 Transient thermal heat source behaviour in experimental setup for an autonomously switching heat bridge. A step change in thermal input power is the input variable

warming up of the structure. With a permanently closed transfer path ("closed gap"), a stationary state was achieved after a delay. Direct coupling of the shape memory element to the heat source, in turn, led to rapid warming up due to the isolation of both source and sink. Reaching the activation temperature in the actuator material closed the air gap, and heat can dissipate into the sink. After reducing the heat supply to 0.7 W, as a consequence, in this case autonomously influenced, the temperature quickly dropped back to the initial state. In the permanently closed case, the final temperature dropped more dramatically (Neugebauer et al. 2012).

17.3.3 Switchable Thermal Conduction Based on Magnetorheological Fluids

Magnetorheological fluids (*MR fluids*) are suspensions of ferromagnetic particles in a carrier fluid that demonstrate significant changes in properties under the influence of an external magnetic field. Whereas most prior investigations and applications of these suspensions mainly focussed on the mechanical properties that are influenced, here the thermal characteristic parameters were considered as a function of the magnetic field. When generating a magnetic field, the magnetic particles of the fluid form chain- or column-like structures. As a result, an anisotropic heat-conducting structure of increased thermal conductivity k_{II} forms in the direction of the magnetic field. Heat transfer is significantly lower if the particles in the fluid are sedimented, for instance, due to the influence of gravity, thus forming two separate layers.

Theoretical preliminary studies by Bruggeman (1935) permit a prediction of thermal conductivity in the uninfluenced state. Reinecke et al. (2008) describe a model for a fluid influenced by a magnetic field. This thermal conductivity depends on the volume content of particles in the overall fluid Φ and the thermal conductivity of the materials used.

Intensity of the magnetic field does not directly affect the model but it can be considered by describing the packing fraction inside the particle chains that increases with field intensity. The model is structured in two stages and, first, the thermal conductivity in the chains k_{chain} under the influence of the magnetic field is calculated by using (17.3). This thermal conductivity is then used in a parallel connection to the surrounding fluid according to (17.4) to determine the effective overall conductivity of the fluid k_{II}. The volume fraction of particles inside the chains Φ_{int} is used as a variable parameter for model adjustment. Extending this approach, it is also possible to predict heat transfer in a deposited fluid: first, a value k_{sed} is determined for the deposited layer with particles with a fraction Φ_{int}, and this is evaluated in comparison with the pure fluid layer in series connection according to (17.5).

$$\left(\frac{k_{chain} - k_p}{k_{base} - k_p}\right)\left(\frac{k_{base}}{k_{chain}}\right)^{1/3} = 1 - \phi_{\text{int}} \tag{17.3}$$

$$k_{II} = k_{base}\left(1 - \frac{\phi}{\phi_{\text{int}}}\right) + k_{chain}\left(\frac{\phi}{\phi_{\text{int}}}\right) \tag{17.4}$$

$$k_{II} = \left(\frac{1}{k_{base}}\left(1 - \frac{\phi}{\phi_{\text{int}}}\right) + \frac{1}{k_{sed}}\left(\frac{\phi}{\phi_{\text{int}}}\right)\right)^{-1} \tag{17.5}$$

An experimental setup was designed to determine thermal conductivity. In the setup, the temperature difference between a heat source and sink was measured in thermal equilibrium under a constant heat supply both with and without a magnetic field. Investigating several samples made it possible to show the functional principle of increased thermal conductivity due to the influence of the magnetic field. The results also outlined the influence of the particle volume fraction. However, in the case of very high volume fractions, the difference between the two switching states is diminished. This can also be explained by the model, since the volume fraction in the chains or deposited layers is limited by the possible packing fraction. If the total volume fraction of particles in the suspension is equal to the maximal packing fraction, then the suspension's thermal conductivity can no longer be influenced because no variation of particle density can be achieved. In Fig. 17.7, the predictions by the model are compared with the values measured for spherical iron particles in silicone oil. The values influenced by the magnetic field were measured at a magnetic field intensity of 105 mT, while the deposited state was reached after a latent period of at least 12 h.

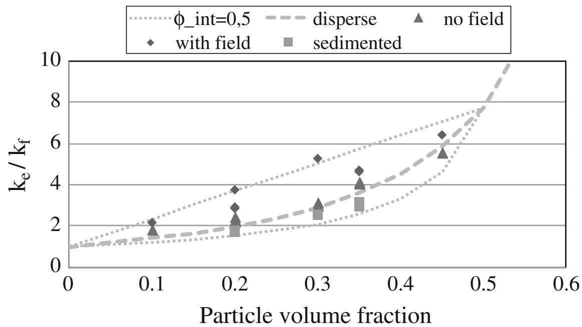

Fig. 17.7 Thermal conductivity as a function of the particle volume fraction, related to thermal conductivity of the basic fluid. Theoretical (*dashed curve* for disperse case, *dotted curves* for magnetic field influence and deposited fluid at an internal volumetric fraction of 0.5) and measured values (*check marks*) for thermal conductivity, scaled to the basic fluid's thermal conductivity

17.4 Classification in the CRC/TR 96

The thermal behaviour of individual components and parts can be actively or passively influenced by the materials and the composite materials investigated, and thus, the overall thermal behaviour of a machine tool can be enhanced. More and more partially heterogeneous thermal behaviour is to be expected due to increasing lightweight construction, as well as anticipated measures towards more energy-efficient utilisation of machine tools, such as switching off subsystems and units during breaks in machining and, as a result, reducing thermal basic load. It is possible to decrease these inhomogeneities by means of the functional mechanisms of compensation investigated here. A lower range of variation in the temperature field reduces the effort required for correction methods to compensate for thermally induced errors in the TCP. The temperature field can be stabilized particularly at positions with a substantial entry of dissipated power and strongly varying heat sources, such as in feed drives, bearings or electronic components.

17.5 Outlook

In future project steps, switchable thermal conduction based on shape memory alloys will first be investigated in more detail. The focus will be on maximizing the switching effect and on an investigation of the behaviour as a control system. Both approaches to switchable thermal conduction have to be evaluated in terms of their applicability according to the requirements in frame structures.

The composite structure consisting of PCM and metal foam will be explored in more detail in co-operation with subproject A07 (see Chap. 9). The diffuse domain method allows for easy discretization of complex geometries. The characteristic values of a metal foam-PCM composite structure determined by means of this method are to be compared both to the simulation results based on the simplified material model and to experimental data.

Finally, the combination of the working principles of thermal storage and variable thermal bonding are to be verified in experiments, and the consequences to the thermal field of a predefined machine structure will be simulated.

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