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Research Paper

Reduced material model for closed cell metal foam infiltrated with phase change material based on high resolution numerical studies

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HIGHLIGHTS

- Closed cell metal foam sandwich structures were investigated.
- High resolution numerical studies were conducted using CT scan data.
- A reduced model for use in commercial FE software reduces needed degrees of freedom.
- Thermal inertia is increased about 4 to 5 times in PCM filled structures.
- The reduced material model was verified using experimental data.

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ABSTRACT

The thermal behaviour of closed cell metal foam infiltrated with paraffin wax as latent heat storage for application in high precision tool machines was examined. Aluminium foam sandwiches with metallically bound cover layers were prepared in a powder metallurgical process and cross-sectional images of the structures were generated with X-ray computed tomography. Based on the image data a three dimensional highly detailed model was derived and prepared for simulation with the adaptive FE-library AMDiS. The pores were assumed to be filled with paraffin wax. The thermal conductivity and the transient thermal behaviour in the phase-change region were investigated. Based on the results from the highly detailed simulations a reduced model for use in commercial FE-software (ANSYS) was derived. It incorporates the properties of the matrix and the phase change material into a homogenized material. A sandwich-structure with and without paraffin was investigated experimentally under constant thermal load. The results were used to verify the reduced material model in ANSYS.

1. Introduction

In high precision mechanical engineering thermal deformations have a large impact on machining accuracy. The fraction of geometrical errors attributed to thermal effects caused by inner and outer heat sources stayed constant in the last decades at about 70–75% [1,2]. While active cooling mechanisms are well established for temperature control to counteract these problems, they are responsible for a large share of energy consumption of the tool machine. In order to increase the energy-efficiency, standby-concepts which allow for a deactivation of basic loads such as the cooling system are a promising approach yet they have the disadvantage of putting the thermal stability and therefore the accuracy of the tool machine at risk [3]. Solutions that reduce the impact of thermal effects on the accuracy without large demands for energy could solve this problem.

Phase change materials (PCM) offer the possibility to stabilize thermal behaviour by providing an increased thermal inertia in its melting range. The latent heat of the phase change enables the material to store or release large amounts of heat over a narrow temperature range [4]. The application of increased thermal inertia is being investigated and used in civil engineering to smooth the temperature variation in interior spaces, as cooling or heating element in transport and storage containers [5] and as heat sink for electronic components [6,7].

Due to the low thermal conductivity of most PCMs and especially paraffin based ones, a non-uniform heating inside a storage volume occurs with the melting interface moving away from the heat source. This leads to a limitation in terms of absorbable or releasable heat per time. Another typical problem with solid–liquid phase change is the mechanical stability of the material as well as the volume change during the melting process [7]. Paraffin-based

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PCMs show a volume expansion in the order of 10%. A common approach to counteract these problems is encapsulation of the material or the usage of additives with high thermal conductivity. For an overview of published research on different approaches, see References 8 and 9. Notably Mills et al. [6] used expanded graphite as matrix material in a cooling concept for Li-Ion battery packs, metallic meshes were considered by Shuja et al. [10] and SiC ceramic honeycomb by Li et al. [11]. While open cell metal foams also received some attention [12,13], closed cell foams are also a viable, yet not well investigated option. Wang et al. [4] conducted experiments on paraffin/aluminium foam composites showing an improvement in melting time and temperature distribution in the composite PCM while they recommend the development of thermal models to simulate the heat storage process of the composite.

Closed cell metal foam is suitable as matrix material due to micro cracks in the walls of the individual pores, making infiltration of liquid paraffin based PCM into the pores of closed cell foam possible. The composite thermal storage exhibits a good mechanical stability while improving the thermal performance. Metal foams are a material class with low densities and novel mechanical, thermal, electrical and acoustical properties [14]. Furthermore a powder-metallurgical production method for the metal foam allows for the production of layered structures with cover sheets. The resulting aluminium foam sandwiches (AFS) provide a good thermal interface surface between heat source and storage.

The aim of the present work is to develop a material model based on the material parameters of the foam and the PCM to predict the thermal performance of a paraffin/aluminium foam composite in finite element software. Due to the size of machine tool structures, a discretization fine enough to represent the individual pores of the foam structure is not viable since it would lead to a very large number of degrees of freedom and thereby to very large computation times. Therefore a high resolution numerical study using data from computed tomography is performed and used to derive a reduced representation of the thermal storage compound. In particular the thermal conductivity as a function of the porosity of the foam is of importance since the correlation of these two parameters is not linear [15]. The resulting homogenized material model for the composite is then validated experimentally with paraffin/aluminium foam structures.

2. Simulation

2.1. Preparation of samples and geometry

Aluminium foam sandwiches (AFS) produced in a powder-metallurgical process according to the procedure described by Seeliger [16] were used for simulation and experiments. The basic material made from aluminium powder (AlMg3Si6) and a foaming agent (TiH2) is placed between two sheets made of Al 6082. The foaming is performed at 600 °C for 25 minutes, resulting in an expansion of the middle layer. The procedure leads to a core metallically bound to the cover layers. Afterwards the sandwich sheets are planed by rolling and cut into the desired dimensions.

In order to perform a high resolution finite element analysis on a realistic foam structure, a 12 mm wide slice was cut from an AFS-sheet with a total thickness of 12 mm made from 1 mm thick cover layers and 10 mm foamed core, as shown in Fig. 1. The sample was scanned with a GE v|tome|x s 240 micro computed tomograph resulting in images with a resolution of approximately 0.02 mm per pixel over a size of 880×897 pixels with the sample being represented by a total of 600 slices. The cover layers were analysed on the basis of the CT-scan. The top cover layer (top side in Fig. 1a) showed the first porosity after 0.61 mm (Fig. 2a and b), the distance between the last porosity and the end of the second cover layer was measured as 0.83 mm. Thus the originally 1 mm thick cover

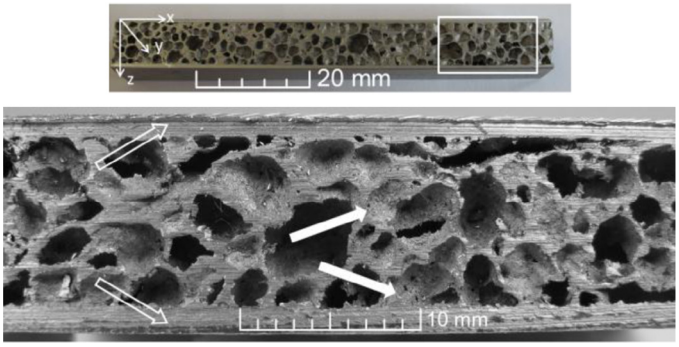

Fig. 1. Top: Slice of AFS used for CT scan, black border indicating scanned volume. Bottom: Detail with cover layers (hollow arrows) and pores including microcracks (filled arrows).

layers were reduced in thickness during the foaming process. Looking at the slice 1 mm below the beginning of the first cover layer (Fig. 2c) a fully developed foam structure is visible, indicating a relevant amount of the cover sheet metal to be partially molten. Therefore a clear separation between the 1 mm thick cover layers and the foam core is not adequate.

The set of CT scan slices was used to create a 3D voxel file. By using the AMDiS meshing tool Meshconv a signed-distance function $r(x)$ (Fig. 3a) was obtained from the voxel-data, denoting the distance between $x \in \Omega$, where Ω is the computational domain. The interface Γ is denoted by the zero-level set of $r(x)$. The PCM phase is labeled with Ω_{PCM}, the aluminium phase with Ω_{Alu} and $r(x)$ is assumed to be negative in Ω_{PCM} and positive in Ω_{Alu}. From this representation, the porosity of the sample could be evaluated for two partial volumes which are investigated in the following simulations. The first volume has a porosity p of 70.7%, the second one 62.4%. For the calculation process with a finite element toolbox like AMDiS [17] an implicit representation by phase field values is required (diffuse domain approach) which can easily be constructed from the signed distances as follows [18]:

$$\Phi(x) = \frac{1}{2}\left(1 - \tanh\left(\frac{3r(x)}{\varepsilon}\right)\right) \tag{1}$$

where ε to be 0.005 is proportional to the interface thickness, $\Gamma = \left\{x \middle| \Phi\left(x = \frac{1}{2}\right)\right\}$ and $\Omega_{PCM} \approx 1$ and $\Omega_{Alu} \approx 0$; see (Fig. 3b). The volume is meshed with a tetrahedral volume-mesh (Fig. 3c), where at least five grid points are guaranteed in the interface.

2.2. Equations

The relaxed linearization scheme by Reference 19 is adopted to solve an enthalpy-based nonlinear heat equation

$$\partial_t H(T) + \nabla \cdot (\mathrm{k}\nabla \mathrm{T}) = 0, \text{in } \Omega \tag{2}$$

with appropriate initial and boundary conditions. Here H and T denote the volumetric enthalpy and temperature, respectively. Through the diffuse domain approach, the thermal conductivity k of each phase can easily be interpolated to

$$k = k_{PCM}\Phi + (1-\Phi)k_{Alu} \tag{3}$$

where k is assumed to be temperature independent. The same way the temperature dependent enthalpy in each phase is calculated from the heat capacities of aluminium and PCM, with