Materials and Design 156 (2018) 42–51

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Investigation of heat transfer in a copper-infiltrated tool steel based on measurement, microtomography, and numerical simulation

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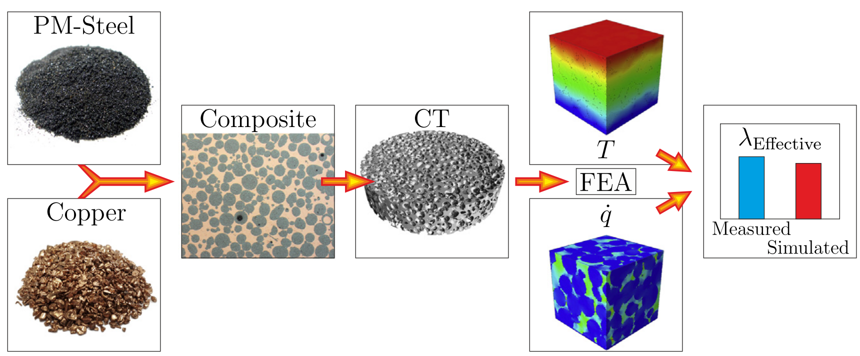
HIGHLIGHTS

- In the investigated copper-infiltrated steel 17% of heat flows through the steel.
- The thermal boundary conductance was numerically approximated.
- The thermal conductivity of the steel is crucial for preventing bottlenecks.
- The nature of the interface influences effective conductivity by up to 27%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form 13 June 2018
Accepted 15 June 2018
Available online 21 June 2018

Keywords:
Thermal conductivity
Thermal boundary conductance
Composite material
Infiltrated steel
Tool steel
Finite-element analysis

ABSTRACT

Copper-infiltrated tool steels potentially combine the good mechanical properties of tool-steels and the superior electrical and thermal conductivity of copper. However, their effective properties greatly depend on the constitution of the components as well as their topology. In this work, the copper-infiltrated cold-work tool steel of type X245VCrMo9-4-4 is analyzed. The thermal conductivity (TC) of the composite and its components is measured and their topology is analyzed by means of X-ray microtomography (μCT). Using the digitized topology and the attained properties, numerical FE simulations were laid out, which allowed the detailed investigation of heat transfer in the material. The results indicate, that 1) the simulated thermal conductivity is very sensitive to the assumed thermal boundary conductance (TBC) 2) the TBC can be approximated by iteratively converging the simulation results to the measured TC 3) both components contribute to the effective thermal conductivity (1/6 steel + 5/6 copper) and act as a bypass for each other, preventing hot spots 4) small increases in the copper content increase the TC by shortening the effective heat conduction path.

1. Introduction

The thermal conductivity of composite materials provide can be tailored for a particular application by varying the selection and constitution of the components as well as their volume content and topology. To do this, the sweet spot has to be found either with great experimental effort or by calculation or simulation using accurate models. This becomes even more important when the aim is to influence multiple properties of a composite material in an optimal manner.

The relation between the properties of a composite and the properties of its components were the subject of many scientific publications. Early researchers investigated these relationships mathematically, which resulted in the well-known effective medium

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https://doi.org/10.1016/j.matdes.2018.06.028
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theories (EMT), most notably from Maxwell [1], Wiener [2], Lichtenecker [3] and Bruggeman [4], which were later enhanced by Landauer [5], Hasselman and Johnson [6], and many more. All these theories rely on different assumptions, thus their validity depends on the real topology of a given material and its agreement with these assumptions. Most of them allow only two components and presume a dispersed, homogeneous distribution of many spherical particles of one phase in the other, which also limits the volume content of this phase to be less than 30%. The influence of interfaces is not commonly considered (except i.e. by Hasselman and Johnson [6]), which excludes a major influence in many real materials.

These problems are addressed by more specific models, i.e. for fiber materials or foams, which introduce even more assumptions originating from the peculiar characteristics of the materials. For spherical inclusions, classical EMT provide good accordance for small volume fractions of homogeneously distributed spheres. If the spheroid content is increased, the spheres eventually touch and may subsequently form a network on their own. Consulting the originally geographic discipline of percolation theory, this point is called the percolation threshold [7]. Since this network can provide a significant contribution to the overall thermal conductivity, the accuracy of the classic EMT diminishes above this threshold, and the influence of interfacial effects becomes even more important.

This means that only a few models exist which accurately represent composite materials that are based on a sintered base body, such as the investigated copper-infiltrated steel. Here, due to the nature of the production method, both components form networks and the spherical phase provides at least 65 vol % of the composite. As a consequence, this leads to a poor accuracy of EMT for the investigated composites, which was observed earlier in a similar case [8]. In the present study, this problem was further investigated by the creation of similar composite materials with different phase ratios that were analyzed with respect to the constitution of their components and the physical properties of the components and the composite. However, for a deeper understanding, the topology of the composites has to be discussed.

The evolution of microtomography (μCT) and meshing algorithms allows the accurate representation of the topology of materials [9-14] by mesh. This has previously been utilized to simulate the behavior of materials like foams (Wejrzanowski et al. [15], Fan et al. [16], Bodla et al. [17]), fiber composites (Evans et al. [18]) and MMCs (Watson et al. [19], Arzbacher et al. [20]). In this work, the topology of both networks was characterized using X-ray computer tomography and was used to simulate the static conduction of heat in the composite. This technique was then employed to estimate the interfacial thermal resistance of the steel/copper interface. Furthermore, the influence of differences in the topology on heat conduction and the effective thermal conductivity was investigated. This correlation of topological properties and heat conduction will be useful for sophisticated future models for the effective properties of similar composites.

2. Materials processing and methods

2.1. Materials

For the following investigation, a copper-infiltrated cold-work tool steel was manufactured and characterized. It is based upon the commercially available steel X245VCrMo9-4-4 (in short X245) and has composition given in Table 1. It was provided as a gas-atomized, spherical powder. The fraction between 63 μm and 80 μm was used for further processing and was obtained by sieving.

Industry-graded, hot-isostatically pressed material based on the same steel was used as a reference and is referred to as X245-HIP. Ir represents the state of the steel in the later composite materials.

Table 1
Chemical composition of the steel X245-HIP in [mass-%], measured using OES.

Fe	V	Cr	Mo	C	Co
Bal.	8,496	4,45	3,615	2,441	1,837
W	Si	Mn	Ni	N	
1,02	0,535	0,409	0,222	0,1217	

To characterize the properties of the copper network, a lab melt was manufactured with the same composition as the network (measured using EDS, see Section 2.2.1). This was achieved by mixing electrolytic copper powder with 3.27 mass-% iron followed by remelting at 1200 °C for 30 min in a graphite-coated Al_2O_3 crucible in a 100 mbar Ar atmosphere. This alloy will is denoted $CuFe_3$.

2.1.1. Sintering and infiltration

To create steel bodies with a different porosity and to allow the creation of composites with different phase ratios after infiltration, the same steel was sintered with different parameters, which are given in Table 2. At the lowest temperature, no liquid phase is formed. Increasing the sintering temperature increases the amount of liquid phase forming during the process. Because of this, the occurring sintering mechanism changes from pure solid-state sintering to partial supersolidus liquid-phase sintering.

After cooling the sintered bodies, they were infiltrated with copper. This was achieved by placing copper, in an amount adjusted to the porosity, on the body that still resides in the crucible. Both are then heated above the liquidus temperature of the copper (1084 °C) so that the copper melts. This liquid is then sucked into the open porosity of the steel body due to capillary force. When this process is finished, the body is cooled so that the copper solidifies and the desired composite is formed. The detailed steps were:

- Placement of 200 g steel powder in zirconia-coated steel crucibles with an inner diameter of 40 mm.
- Sintering of the steel body. Drying at 300 °C and reduction at 1000 °C, both for 30 min in a moderate vacuum. The sintering parameters are given in Table 2 for an atmosphere of 1 mbar Ar. After sintering, the bodies were furnace-cooled to ambient temperature.
- Placement of the proper amount of electrolytic copper on the steel body.
- Infiltration with copper. Again drying at 300 °C and homogenizing at 1000 °C for 30 min in a moderate vacuum. The body was heated to 1120 °C to melt the copper and start the infiltration process. This step was performed in a 100 mbar argon-atmosphere to prevent evaporation of copper; the temperature was maintained for 10 min. The composite was then furnace-cooled to room temperature.

2.1.2. Heat treatment

The same heat treatment was applied to all specimens of X245-Cu(1-4) as well as X245-HIP and $CuFe_3$. First, all specimens were

Table 2
Parameters used for sintering and the achieved porosity, which was determined according to Section 2.2.2.

Material	Temperature [°C]	Duration [min]	Porosity [vol%]
X245-Cu1[a]	1260	30	13
X245-Cu2	1260	30	16
X245-Cu3	1250	30	23
X245-Cu4	1200	60	31

[a] Powder was not fractionated.