Acoustic-Pressure-Assisted Engineering of Aluminum Foams

Xavier Mettan, Edoardo Martino, Lidia Rossi, Jačim Jačimović, Juraj Krsnik, Osor S. Barišić, Norbert Babcsán, Sándor Beke, Rajmund Mokso, George Kaptay,* and László Forró*

1. Introduction

A metal foam is an arrangement formed of gas cells trapped in a solid-metal matrix, and it presents two tangible-technological advantages over its bulk counterpart. First, by tuning the size, volume fraction, and shape of the bubbles, the composite mechanical, electronic, and thermal properties can be tailored according to the desired function of the resulting material.[1,2] In many cases, this leads to a blend of the original material’s properties with new features, augmented by the lightweight. The latter doubly profits by lowering the imprint of the foam parts in a mechanical assembly and reducing the amount of raw material, hence diminishing its cost, which is also a strategic requirement.[3]

Applications of metal foams are versatile, because they combine attractive features of metals, such as high electrical and thermal conductivities and good mechanical properties with lightweight and large surface-to-volume ratios.[4–6] Among many existing applications, different metal-matrix-foam materials serve as heat exchangers, bodyworks, sound absorbers, electromagnetic shielding elements, and catalysts in various sectors, such as automotive, buildings, or aerospace.[7,8] Aluminum alloys stand out as the most popular matrices for metal foams. Abundance of aluminum on Earth, its low density, good mechanical properties, and resistance to corrosion make these alloys good candidates for foaming. In addition, aluminum ranks as a low-melting-point metal, rendering its processing easier, demanding less power compared with, e.g., titanium or steel.

Due to this large interest in metal foams, several methods for foaming have been developed. That is, numerous processes have been demonstrated to achieve foaming of aluminum alloys, such as direct-gas-injection methods, preparation from metallic powders containing a blowing agent (a convenient one is TiH2[9]), or infiltration of the matrix into spaceholders. The latter permits a
rather precise control of the cells geometry and spacing; however, only open-cell configurations are achievable, and the process involves many complex steps. Production from metallic powders is easier to implement, but prevents a precise and low-cost tailoring of the cells dimensions.\cite{12}

A direct injection of a gas into liquid aluminum is a well-known and straightforward route to create bubbles, where control on the shape of the foam can be exerted via injection-nozzle diameter and nozzle-wetting characteristics. Precisely controlling the size and distribution of the cells is crucial when optimizing the properties of a foam for a targeted application. However, while tuning of the foam morphology is possible by adapting the hardware or changing the composition of an alloy, none of the established foaming techniques can yet allow for direct, in situ control of the foam morphology. Providing a way to spatially engineer the distribution of cell’s sizes would be beneficial to targeted applications, in particular, to enhance the structural strength of mechanical parts.

Here, we give a theoretical description of an acoustic-enhanced control of the size of the bubbles in an aluminum melt. A representative aluminum sample engineered with acoustic pressure is displayed in Figure 1, showing a rather uniform bubble size distribution. To further verify our model to control the foam parameters, we have experimentally investigated the process by means of synchrotron-based X-ray imaging, yielding the bubble size distribution as a function of the experimental parameters. The beauty of our method is that it is not restricted to aluminum melts. Instead, it could be applied to a variety of other systems. In fact, the only requirement is to have a foamable phase with cell walls stable against external perturbations. Knowing the density of the foamable liquid and the diameter of the injector permits an estimate of the span of bubble diameter reachable by this method.

In addition, for one type of aluminum foam, we have performed the characterization of electrical and thermal transport coefficients: electrical resistivity ($\rho$), Seebeck ($S$) coefficient, and thermal conductivity ($\kappa$) in a broad temperatures range. Our results suggest that material foaming could be a good strategy for application in thermoelectric energy conversion. Because of the fine-tuning of all transport coefficient and enhancement of the Seebeck coefficient, we have observed an improvement in the efficiency for thermal to electrical energy conversion, quantified by the thermoelectric figure of merit $ZT$. The promising target alloys could be topological insulators and Heusler alloys.\cite{13,14}

2. Experimental Section

2.1. Materials

In our study, we focus on a commercially available aluminum metal-matrix composite (MMC) called Duralcan F3S.20S, that contains 20% in volume of SiC particles of 20 $\mu$m diameter (Chemical composition of F3S.20S in %wt: Si:9.2, Fe:0.12, Mn:0.02, Mg:0.54, Ti:0.10, Al:balance, SiC:20.8). These solid particles are known to stabilize the foams in the liquid state because of the action of interfacial capillary forces.\cite{9} Foams made by these MMCs also have improved stability and can be manipulated and solidified to form any shape.\cite{13,14} They are popular in industry owing to their low density and good mechanical properties.

2.2. Methods

The samples of metal foams were fabricated according to the method presented in the previous study\cite{15} as shown in Figure 2a. Liquid Duralcan was held in a heating crucible at a temperature of 700 $^\circ$C. Gas (argon 4.6) was injected at controlled and regulated (PID) flow at a pressure of 2.5 bar through the melt via a nozzle coupled to an ultrasonic-wave generator, called sonotrode, placed at the bottom of the crucible, and with its longitudinal axis pointing upward. The orifice of the sonotrode has a diameter $D_1 = 0.2$mm, and the external diameter of the circular sonotrode is $D_2 = 4$mm. A 30 kHz ultrasonic generator (Woodpecker UDS-N1) delivering up to 160 W cm$^{-2}$ of acoustic power and a piezoelectric transducer (titanium waveguide) were used to pulse acoustic waves through a steel injector, so that the injector vibrates along its longitudinal axis (vertically). The characteristic bubble size $D(P_{\text{el}})$ was measured as the function of the control parameter, $P_{\text{el}}$, being the electrical power (0–20 W) fed to the sonotrode.\cite{16} In addition, the differential pressure prevailing at the orifice of the nozzle, called dynamic pressure, was

Figure 1. a) Microscopy image of a Duralcan aluminum foam prepared by acoustic pressure assistance. b) The histogram based on the image analysis reveals the reasonably uniform bubble sizes.
monitored as a function of time. A differential-pressure sensor (Motorola MPX5050DP) connected to the steel injector provides a voltage signal to custom acquisition electronics, with 5 Pa accuracy and with 500 kHz sampling rate. In a steady-state regime, when bubbles form and detach at a constant rate, the dynamic pressure oscillates with a period corresponding to the time of formation of a bubble $t_b$. Knowing the constant gas-flow rate $Q$, the volume of the bubble is determined as $V_b = \frac{Q}{C^2} t_b$. The broad range of bubble size as a function of acoustic pressure, translated to sonotrode power, is used to support the theoretical description.

High-brilliance and high-coherence X-ray beam (TOMCAT beamline at the Swiss Light Source, Paul Scherrer Institute) allows micro- and sub-micrometer, quantitative, 3D imaging at high frame rate and extends the traditional absorption imaging technique to edge-enhanced and phase-sensitive measurements. In the current study, the probe was a broadband X-ray beam with energy centered around 20 keV ($\lambda \approx 0.06$ nm). The foaming furnace was placed in the X-ray beam in front of a 500 μm thick YAG:Ce scintillator coupled to a high-speed camera (PCO Dimax) optimized for sub-millisecond recording. The formation of bubbles in the melt was monitored by pressure measurement simultaneously with the X-ray radioscopy at 1400, 6600, and 10 000 fps with a pixel size of 11 μm. To determine the diameter of bubbles, still images were analyzed with ImageJ v.1.43u with 2% accuracy; the diameter of the nozzle was used as a scale reference (rectangle highlighted in Figure 2b,c). Such measurements of diameters were repeated for at least ten times, from two perpendicular angles of view with respect to the nozzle, yielding a statistical average for diameters at various acoustic pressures. The size of bubbles was adapted by the acoustic pressure, generated by the sonotrode in the liquid metal (Figure 2b,c).

2.3. Acoustic-Pressure-Induced Detachment of Gas Bubbles in a Liquid

Here, we assess the influence of acoustic pressure on the size of bubbles in a liquid, and we introduce a general model for their acoustic modulation, which can be applied to different liquids. First, a common model for determining the size of bubbles in a liquid under static-pressure conditions is recalled, after which we introduce an effective contribution for dynamic modulation. We consider a situation with a cylindrical nozzle, pointing upward and submerged in a liquid (Figure 3). The nozzle can inject gas in the liquid at a controlled flow rate and pressure. Typically, at low flow rates, a bubble starts to form at the orifice and grows to a special shape close to that of a sphere before it detaches from the orifice.

In Figure 3, an idealized situation, just before detachment of the bubble, is shown. The bubble is considered symmetrical around the vertical axis parallel to the nozzle. At this instant, a simple force balance allows us to predict the characteristic diameter $D$ of the bubble after detachment, supposing it has a spherical shape. First, the buoyancy force $F_b$, pointing upward, tends to detach the gaseous bubble from the nozzle

$$F_b = g(\rho_l - \rho_g) V_b$$

(1)

where $V_b$ is the volume of the bubble, $g = 9.81 \text{m s}^{-2}$ is the gravitational acceleration, and $\rho_l$ ($\rho_g$) is the density of the liquid.
The volume of the bubble is modeled through its diameter just after it detaches from the orifice. As \( \rho_b \ll \rho_l \), the buoyancy force in Equation (1) is simplified as \( F_b = \frac{\pi}{6} \rho_b g D^3 \). Opposed to \( F_b \), the interfacial antistretching force acting at the neck of the bubble is modeled as\([17]\)

\[
F_i = -L_i \gamma ^#
\]

where \( \gamma \) is the surface tension of the liquid, and \( L_i = \pi D_i \) is the inner perimeter of the orifice measured along the horizontal plane, perpendicular to the direction of the stretching buoyancy force.\([18]\]

It is appropriate to consider the inner perimeter \( D_i \) when the liquid wets the material of the orifice. Writing \( F_b + F_i \geq 0 \) (at the instant of detachment), the characteristic diameter of a bubble can be obtained by substituting Equation (2) into the latter condition

\[
D^* \geq \left( \frac{6 \rho_b \gamma}{\rho_l \ell} \right)^{1/3} #
\]

which can be verified experimentally. The superscript "0" denotes the absence of any additional external forces. If one inserts \( \rho_l = 2300 \text{ kg m}^{-3}, \gamma = 0.86 \text{ J m}^{-2} \) of oxidized liquid aluminum into Equation (3) with the applied inner nozzle diameter of 0.20 mm, the value of \( D^* \) = 3.6 mm is obtained. This is the boundary condition (maximum value) of the detaching bubble size from this nozzle in absence of applied sonotrode power. This value is in agreement with data at zero pressure, as shown in Figure 4b.

One can notice that, in Equation (3) for a given liquid, only \( D_i \) enables the control of the size of the bubbles. However, in applications, this quantity cannot be tuned in situ, especially in challenging conditions of high-temperature melts. To overcome these technological limitations, we introduce an additional force acting on the bubble, promoted by acoustic pressure. Conveniently, the submerged orifice can be a nozzle combined with a sonotrode device (see Figure 2), whose vibrating power and frequency can be electronically actuated. As a first approach, we consider an additional effective force \( F_a \) opposing the interfacial antistretching force, so that the new condition for the bubble to detach from the orifice is: \( F_b + F_i + F_a \geq 0 \). The force \( F_a \) applies on the projection of the surface of the bubble not covered by the nozzle \( A_p = \pi (D^2 - D_i^2)/4 \) and can be written as

\[
F_a = p \cdot A_p = p(P_{el}) \cdot \pi (D^2 - D_i^2)/4
\]

where \( P_{el} \) is the electrical power of the frequency generator supplied to the sonotrode via the piezoelectric transducer, \( p = p(P_{el}) \) is the acoustic pressure, and \( D = D(P_{el}) \) is the control parameter-dependent bubble diameter. Finally, the balance equation for the bubble diameter \( D \) in a nozzle-wetting liquid is

\[
g \rho_l D^3 + \frac{1}{2} p(D^2 - D_i^2) - 6 D \gamma = 0
\]

Equation (3) is obtained back from Equation (5), fulfilling the boundary condition: at \( p(0) = 0, D(0) = D^0 \). A formulation of \( p(P_{el}) \) can be made recalling simple concepts. The actual power density transmitted to the liquid is \( I_s = \eta P_{el} \), where \( 0.1 \leq \eta < 1 \) is a transmission efficiency, and \( A_s = \frac{\pi}{4} (D^2 - D_i^2) \) is the area of the sonotrode in contact with the liquid and perpendicular to its oscillation direction. The actual pressure reflected\([17]\) on the liquid–gas interface is

\[
p_{ar} = 2 \frac{L_i}{v_s} = 2 \eta \frac{P_{el}}{v_s}
\]

Here, \( v_s \) is the speed of sound in the liquid medium, and the factor 2 stems from the complete reflection of the sound wave at the liquid–gas interface.\([19-21]\]

Finally, the acoustic pressure \( p \) can be written as

\[
p(P_{el}) = k_{eff} \cdot p_{ar} = k_{eff} \cdot \frac{1}{v_s} \cdot \frac{8 \rho_l}{\pi (D^2 - D_i^2)} \cdot P_{el} = b \cdot P_{el} #
\]

where the only dependence on the liquid type is in \( v_s \). The parameter \( k_{eff} \) accounts for damping inside the liquid.\([22]\) For example, for a sphere with large Reynolds number, \( k_{eff} \approx 0.4 \).\([23]\]

As shown in Figure 4a, the acoustic pressure can be modeled by the form proposed in Equation (7). In this manner, the fitting parameter \( b \) provides an estimation for the diameter of the bubble as a function of \( p = b P_{el} \). The bubble diameter \( D \) as a function

Figure 4. a) Showing the linearity of \( p(P_{el}) \) with \( P_{el} \) in the spirit of the model of acoustic pressure. The solid line corresponds to Equation (7), with \( b = 2.5 \text{ Pa W}^{-1} \). b) Collected data of bubble diameter as a function of the acoustic pressure (see Figure 2). The solid line is a fit according to Equation (5). As some of the bubbles have oval shape, the size was measured in two perpendicular directions, and the average value was attributed to \( D \). This sets the error bar of the data. The inset shows the same data in a semilogarithmic representation, to highlight the presence of an inflexion point in the curves, where the formation of a bubble dominated by buoyancy forces is overtaken by the acoustic pressure.
of the acoustic pressure $p$ is shown in Figure 4b for Duralcan. The fitting line for Duralcan fairly agrees with the experiment.

Here, we have shown experimentally and theoretically that applying ultrasonic power to the melt permitted us to control the diameter of bubbles continuously from 3.8 to 0.7 mm. It has significant implications for the fabrication of aluminum foams. First, one can prepare products with customized pore sizes on the same production line, which has obvious cost advantages. Second, materials with custom bubble-diameter patterns can be designed. For example, one could imagine large foam panels with gradient pore diameter, with pores smaller and smaller as they become closer to the surface, a geometry that would favor lightweight and good strength. This could even be more important for sound absorption, where an accurately controlled distribution of the pores would lead to specific acoustic properties. Thermal-flow control could also be enhanced through alternation of large/small pores.

2.4. Measurement of Transport Coefficients

A novel possibility for application of metal foaming could be in thermoelectricity, which is a direct conversion of the waste heat into electricity. As a proof of principle demonstration that foaming could increase the figure of merit $ZT$ of thermoelectric devices, we have measured transport properties of the solidified Duralcan foam with the porosity 76%, and made a comparison to the bulk parent material (before foaming), to the compressed foam, and to the 5 N pure aluminum. In particular, we have found that the foaming increases $ZT$ by an order of magnitude around room temperatures, ascribing this effect to the enhancement of thermopower due to the reduced dimensionality in the disordered environment and electron filtering effects.

The measured samples of foam were cut from a massive block to a typical dimension of $1 \times 3 \times 10 \text{ mm}^3$. The structure and the compositional analysis are shown in Figure 5. The optical and scanning electron microscopy (SEM) images reveal the textured matrices. It can be seen that the sample has closed-cell pores of average diameter of 700 μm; however, their distribution varies somewhat. The SEM and energy-dispersive X-ray (EDX) images clearly show the presence of SiC particles as surfactant, stabilizing the bubbles. Their size is in the 10–20 μm range. One may notice a small quantity of Mg as well, which is a constituent of the Al alloy matrix.

The transport coefficients investigated here are the electrical resistivity $\rho$, the thermopower $S$, and the thermal conductivity $\kappa$. These three coefficients have never been studied for aluminum foam system, and especially not in a broad temperature range involving liquid helium temperatures, which is important for a microscopic understanding of transport properties. The thermoelectric figure of merit is given by

$$ZT = \frac{S^2 T}{\rho \kappa}$$

where $T$ is the temperature, and $\sigma = 1/\rho$ is the electrical conductivity. The $ZT > 1$ are values, above which the material is suitable for thermoelectric applications. Figure 6a–c shows the temperature dependence of $\rho$, $\kappa$, and $S$, respectively, for high purity aluminum (5 N), the bulk Duralcan, the Duralcan foam, and the sample of compressed Duralcan foam where the density is close to the solid composite. To obtain the latter, a small block of foam has been compressed uniaxially with a pressure of up to 0.8 GPa at 200 °C to completely collapse all the bubbles.

The resistivity $\rho(T)$ for pure aluminum in Figure 6a closely reproduces results found in the literature. For Duralcan, using the simple Drude model, the residual resistivity $\rho(T=0)$ provides an estimate of the electron mean-free path of $\approx 20–30 \text{ nm}$. The latter roughly matches the average size of crystallites (30–40 nm). With foaming, the absolute value of $\rho(T=0)$ is shifted to the 60–70 μΩ cm range. The high value of $\rho(T)$ for the foam indicates that in addition to the scattering on lattice vibrations, scattering at bubbles’ surface, at their interconnections, and on the SiC particles strongly alters the electronic mean free path. Interestingly, when the residual resistivity is subtracted from the data, the temperature dependence of the resistivity measurements for all samples may be satisfactorily described by the Bloch–Grüneisen formula, with the Debye temperature of roughly 400 K.

The Wiedemann–Franz law states that $\kappa_{el} = \frac{L_0 T}{\rho}$, where $L_0 = 2.44 \times 10^{-8} \text{ W K}^{-2}$ is the Lorenz number. Using this law, the thermal transport for the pure aluminum may be almost entirely ascribed to the electron subsystem, $\kappa \approx \kappa_{el}$. While the high values of the thermal conductivity $\kappa$ for the pure aluminum in Figure 6c are characteristic for crystalline metals,
κ for the Duralcan samples drops to low values, with a full suppression of the maxima at low temperatures that characterizes κ for the pure aluminum. This kind of behavior of κ, similarly as in the case of resistivity data, suggests that the electrons are strongly scattered. By extracting through the Wiedemann–Franz law, the electronic contribution from the total $\kappa = \kappa_{el} + \kappa_{ph}$, one could extract the phonon-contribution $\kappa_{ph}$. Such kind of an analysis indicates that the relative phonon-contribution to κ is significant only for the foam and comparable to $\kappa_{el}$ at elevated temperatures.

The results for $\sigma$ and κ clearly show a dramatic effect that microstructuring of the material has on transport properties. However, with exceptions of low temperatures, the ratio of these two coefficients in Equation (8) remains similar for all samples. Therefore, in order to rationalize the large enhancement of ZT observed in Figure 6d, we turn to behaviors of S for the bulk Duralcan samples and the foam, shown in Figure 6c, to rationalize the large enhancement of ZT observed in Figure 6d for the foam. The two depict similar temperature dependence, with the local maximum of |S| due to the significant influence of the electron–phonon coupling, although that of the latter has doubled at the room temperature. The origin of this difference can be traced back using the Mott formula

$$S \sim d\ln \sigma / dE = (d\ln \mu(E) / dE + d\ln N(E) / dE)_{E=E_F},$$  

where the first term on the right-hand side represents the energy dependence of the electron mobility, whereas the second is given by the energy dependence of the density of states (DOS). We argue that foaming and the SiC inclusions should greatly enhance the second term. Reduced dimensionality/quantum confinement effects in the foam and many impurity states introduce large variations in the local DOS, thus enhancing the derivative of local DOS with respect to the energy in the vicinity of the Fermi level. Moreover, the electron diffusion part of the thermopower may be additionally increased due to the electron filtering effects where bubbles act as tall barriers. This is an extremely interesting development, because it justifies our conjecture that foaming could be beneficial to increase ZT, as shown in Figure 6d, resulting in an order of magnitude increase for the foam over that of the bulk material. It is plausible that further engineering of the foam could result by even stronger enhancements of ZT.

3. Conclusion

We have modeled the bubble formation by applying acoustic pressure in molten metals, which fully describes the experimental observations of in situ synchrotron-based X-ray radioscopy of bubbles in Duralcan aluminum composites. This method allows fine-tuning of the size of the bubbles that could be stabilized by additives such as SiC particles, leading to castable, highly functional metallic foams.

Performing detailed electronic and heat transport studies of the aluminum foam, we have given a proof of principle that...
foaming a metal could significantly enhance the thermoelectric figure of merit. The class of materials where such a strategy could be highly beneficial are topological insulators and Heusler alloys.

Acknowledgements

X.M. and E.M. contributed equally to this work. G.K. thanks projects TÁMOP-4.2.2.A-11/1/KONV-2012-0036 and GINOP-2.3.2-15-2016-00027 obtained from the Ministry of Innovation and Technology of Hungary. The work in Lausanne was supported by the Swiss National Science Foundation. The technical support of Peter Makk is gratefully acknowledged. J.K. acknowledges the support by the Croatian Science Foundation Project IP-2016-06-7258. O.S.B. acknowledges the QuantIXde Center of Excellence, a project co-financed by the Croatian Government and European Union (Grant No. KK.01.1.1.01.0004). The authors acknowledge the Paul Scherrer Institute for granting experimental time at the TOMCAT beamline (proposal 20100211).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Research data are not shared.

Keywords
aluminum, foams, metal-matrix composites, thermoelectricity

Received: March 14, 2021
Published online: April 14, 2021

[1] L. Viscusi, M. Carrino, A. Durante, Int. J. Adv. Manuf. Technol. 2020, 106, 1683.
[2] M. Styles, P. Compston, S. Kalyanasundaram, Compos Struct. 2007, 80, 532.
[3] J. Banhart, Int. J. Veh. Des. 2005, 2005, 114.
[4] F. García-Moreno, Materials 2016, 9, 85.
[5] N. Dukhan, Metal Foams: Fundamentals and Applications (Ed: N. Dukhan), DEStech Publications, Inc, Lancaster, PA, USA 2013.
[6] J. R. Davis, Copper and Copper Alloys (Ed: J. R. Davis), ASM International, Materials Park, OH, USA 2001.
[7] J. Banhart, Comprehensive Composite Materials II, Ch. 4.14 Production of Metal Foams (Ed: T. W. Clyne), Elsevier, Amsterdam 2018, pp. 347-363.
[8] L. P. Lefebvre, J. Banhart, D. C. Dunand, Adv. Eng. Mater. 2008, 10, 775.
[9] F. García-Moreno, P. H. Kamm, T. R. Neu, F. Büll, R. Mokso, C. M. Schleputz, M. Stampanoni, J. Banhart, Nat. Commun. 2019, 10, 1.
[10] J. Banhart, Progr. Mater. Sci. 2001, 46, 559.
[11] W. Xie, A. Weidenkaff, X. Tang, Q. Zhang, J. Poon, T. M. Tritt, Nanomaterials 2012, 2, 379.
[12] G. Kaptay, J. Dispers. Sci. Technol. 2012, 33, 130.
[13] S. W. Ip, S. W. Wang, J. M. Toguri, Can. Metall. Q. 1999, 38, 81.
[14] B. P. Binks,Curr. Opin. Colloid Interface Sci. 2002, 7, 21.
[15] N. Babcsán, S. Beke, P. Makk, US 9,168,584 B2, 2015.
[16] G. Wang, M. Sathe, S. Mitra, G. J. Jameson, G. M. Evans, Can. J. Chem. Eng. 2014, 92, 2067.
[17] G. Kaptay, Adv. Colloid Interface Sci. 2018, 256, 163.
[18] G. Kaptay, Colloids Surf., A 2003, 230, 67.

[19] When a sound wave travels through a liquid medium and hits a gas- eous bubble, the ratio of the reflected energy density (wr) to the total energy density (w) can be calculated as, wr = (Zg – Zl)/2 with Zg and Zl the impedances of the gas and liquid, respectively. For a water/air interface at 298 K, wr/w = 0.9989, while for aluminium/air at 950 K, wr/w = 0.99992. Thus, for both cases more than 99% of the acoustic energy of the liquid is reflected back by the bubble.

[20] Springer Handbook Of Acoustics (Ed: T. Rossing), Springer Science & Business Media, Berlin 2007, pp. 1197–1197.
[21] H. Kuttruff, Acoustics, An Introduction (Ed: H. Kuttruff), CRC Press, Boca Raton, FL, USA 2007, p. 457.
[22] The force associated to a stream has an effective part, represented by kEff.
[23] Transport Phenomena In Materials Processing (Eds: D. R. Poirier, Geiger, G.), Springer, Cham 2016.
[24] F. Pawlek, D. Rogalla, Cryogenics 1966, 6, 14.
[25] P. Ranut, App. Ther. Eng. 2016, 101, 496.
[26] F. G. Cuevas, J. M. Montes, J. Cintas, P. Urban, J. Porous Mater. 2009, 16, 675.
[27] Y. Feng, H. Zheng, Z. Zhu, F. Zu, Mater. Chem. Phys. 2003, 78, 196.
[28] J. W. Paek, B. H. Kang, S. Y. Kim, J. M. Hyun, Int. J. Thermophys. 2000, 21, 453.
[29] N. Babcsán, I. Mézáros, N. Hegman, Materialwiss. Werkstofftech. 2003, 34, 391.
[30] J. P. Heremans, V. Jovovic, E. S. Toberer, A. Saramat, K. Kurosaki, A. Chareonphakdee, S. Yamancika, G. J. Snyder, Science 2008, 321, 554.
[31] L. D. Hicks, M. S. Dresselhaus, Phys. Rev. B 1993, 47, 12727.
[32] M. S. Dresselhaus, G. Chen, M. Y. Tang, R. C. Yang, H. Lee, D. Z. Wang, Z. F. Ren, J.-P. Fleural, P. Gogna, Adv. Mater. 2007, 19, 1043.
[33] K. Valalaki, P. Benech, A. G. Nassiopoulou, Nanoscale Res. Lett. 2016, 11, 201.
[34] R. H. Tarkhanyan, D. G. Niarchos, J. Mater. Res. 2015, 30, 2618.
[35] J. P. Heremans, C. M. Thrush, D. T. Morelli, Phys. Rev. B 2004, 70, 115334.
[36] D. Vashaee, A. Shakouri, Phys. Rev. Lett. 2004, 92, 106103.
[37] J. M. O. Zide, D. Vashaee, Z. X. Bian, G. Zeng, J. E. Bowers, A. Shakouri, A. C. Gossard, Phys. Rev. B 2006, 74, 205335.
[38] R. P. Huebener, Phys. Rev. 1968, 171, 634.
[39] A. L. Woodcraft, Cryogenics 2005, 45, 626.