Research Article

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Temperature-porosity-dependent elastic modulus model for metallic materials

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Abstract: Elastic modulus plays a key role in the application of porous metallic materials. However, to the best of our knowledge, few attempts have been made to model the simultaneous dependence of elastic modulus on temperature and porosity for metallic materials. The present article contributes to a rational temperature-porosity-dependent elastic modulus model for metallic materials with all parameters having definite physical significance. The model can well predict the elastic moduli of porous metallic materials, from extremely low temperature to ultrahigh temperature, and from dense material to about 0.9 porosity, with reference to an easy-to-access elastic modulus. In a special case, when intrinsic elastic modulus $[M] = 2$ and critical porosity $P_C = 1$, a phenomenological parameter-free predictive model can be obtained. The model can be applied when the matrix Poisson ratio is $0.1 < \nu < 0.4$ for Young's modulus and $0.17 < \nu < 0.27$ for shear modulus, which covers most metallic porous materials.

Keywords: elastic modulus, temperature, porosity, metallic materials

1 Introduction

Porous metal has drawn a great deal of attention in the last decades, and has been extensively used in aerospace, shipping, building, automotive engineering, etc. This is of course owing to their outstanding thermal, acoustic, electromagnetic, and mechanical properties [1–4]. Elastic modulus is one of the most important mechanical properties and plays a key role in the abovementioned application fields. Therefore, immense literature, both in experiment and theory, is available on their porosity-dependent elastic modulus [5,6]. In addition, due to their advantages in heat insulation, packaging, and energy-absorption, porous metals are also widely used in high-temperature service environments, e.g., evaporative cooling rocket nozzle, steam or gas turbine combustors, and thermal protection system of the exhaust port on aircraft [1,7]. Therefore, investigation of the temperature-dependent elastic modulus of porous metals is of great importance in practical application. And numerous research works in this field can also be found. However, to the best of our knowledge, only occasional attempts have been made to confirm the combined effects of both porosity and temperature on the elastic modulus of metallic materials from the side of experiment, and even less attention was paid from the side of theory. Munro [8] proposed a temperature-porosity-dependent elastic modulus model for ceramic materials:

$$E(T, P) = E_0(1 - \alpha T)(1 - P)^n \tag{1}$$

where $E(T, P)$ denotes the elastic modulus at different temperatures and porosities, E_0 denotes the elastic modulus of dense material at ambient temperature, P denotes the porosity, and α and n are the fitting parameters. In this model, the temperature-dependence of elastic modulus is considered by a linear relation. Although the variation in the elastic modulus in certain temperature range above Debye temperature is almost linear [9], the model is not rational at low temperatures, since the slope of elastic modulus vs temperature curve will approach zero as the temperature approaches absolute zero, according to the third law of thermodynamics and experimental results.

Zhang et al. [10] suggested another model for ceramic materials:

$$E(T, P) = (E_0 - BT \exp(-T_D/T))\left(1 - \frac{P}{P_C}\right)^n \tag{2}$$

where B denotes the slope of Young's modulus vs temperature curve above room temperature. T_D is a parameter and suggested to correlate with Debye temperature [9].

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P_C denotes the critical porosity (which can be interpreted as the percolation threshold in percolation theory [11,12]), at which the elastic modulus of porous material reaches zero. And n is a fitting parameter. This model takes a big step forward compared with Munro's model, which can be applied in wide temperature and porosity range. However, due to its intrinsic defect, this model inherits too many phenomenological fitting parameters.

As can be seen from the above actualities, studies on theoretical modeling of elastic modulus with simultaneous dependence on temperature and porosity are still not enough. The present article attempts to make up for the deficiency. In Section 2, we review the porosity-dependent and temperature-dependent elastic modulus model first, and then contribute to a more rational temperature-porosity-dependent elastic modulus model for metallic materials. In a special case, the model can be deduced to be a phenomenological parameter-free predictive one, and is validated by a systematic comparison between the predicted results and available experimental data in a wide range of temperature and porosity. Furthermore, determination of parameters and application criterion of the model are also discussed.

2 Temperature-porosity-dependent elastic modulus modeling

To deduce a reasonable temperature-porosity-dependent elastic modulus model, we carefully investigated previous studies on this theme. Pabst et al. [6] began his modeling process with an assumption that the effects of temperature and porosity on elastic modulus may be separated, and the validations support his assumption. Moreover, the experimental results by Armstrong [13] and Pabst et al. [14] also support that the relative effects of porosity on elastic modulus are independent of temperature. On the contrary, different statements also exist. Werner et al. [15] experimentally studied the influence of porosity on Young's modulus of carbon-bonded alumina from room temperature up to 1,450°C, and found that Munro's decoupling model can be proved valid up to 1,025°C for the composite material. At higher temperatures, the interaction of temperature and porosity should be noted. Following Werner et al. [15], Zhang et al. [10] began their modeling with a conservative consideration that the combined effects of temperature and porosity should be taken into account. Their verification results, however, voted that decoupling of temperature and porosity is suitable. To sum up, decoupling effects of temperature and porosity on elastic modulus may not be suitable for certain materials in high temperature range, but it can be acceptable for the other majority of conditions. Therefore, in this study, we take the following decoupling form for the temperature-porosity-dependent elastic modulus model:

$$E(T, P) = E(T)E(P) \tag{3}$$

where $E(P)$ and $E(T)$ denote the porosity-dependent and temperature-dependent elastic modulus, respectively. And next we need to find suitable model for $E(P)$ and $E(T)$.

2.1 Porosity-dependent elastic modulus model

The porosity dependence of elastic modulus is an important and old theme. There has been much effort dedicating to the understanding of it since 1960s [15]. A great many theoretical and experimental research works have been conducted, and numerous models have been put forward [5,6,16]. However, this does not mean that this old theme has been fully understood. Generally speaking, existing porosity-dependent elastic modulus models can be roughly classified into linear relation, polynomial relation, power-law relation, and exponential relation, and almost all of them are empirical or semi-empirical relations. Although the linear relation, $E(P) = E(P_0)(1 - aP)$ (where a is a fitting parameter), can obtain a good fit with experiment results at certain porosity ranges [17–19], researchers familiar with this field know it for sure that it cannot describe the elastic modulus in a large porosity range, since it is obviously not linear. Other researchers also proposed power-law relation, exponential relation, and other relation forms after observing the variation in elastic modulus with porosity [11,20–23], and different relation forms can well describe the elastic modulus at different porosity ranges [6,8]. However, strictly speaking, there is not much physical significance left in the above-mentioned relations, and the studied elastic moduli are also not zero when $P = 100\%$. In order to satisfy this basic boundary condition and assign physical significance to parameters in the model, Pabst et al. [6] and Pabst and Gregorová [24,25] studied the classic research by Coble and Kingery [26], Mackenzie [27], and Dewey [28], then summarized and improved the expression of Coble-Kingery relation.

$$E(P) = E(P_0)(1 - [M]P + ([M] - 1)P^2) \tag{4}$$

where $E(P_0)$ denotes the elastic modulus of dense material, $[M]$ denotes the intrinsic elastic modulus, $[M] = 3(1 - \nu)(9 +$

$5\nu)/[2(7-5\nu)]$ for Young's modulus, $[M] = 15(1-\nu)/(7-5\nu)$ for shear modulus, and $[M] = 3(1-\nu)/[2(1-2\nu)]$ for bulk modulus, ν denotes the matrix Poisson ratio. In a special case, when $[M] = 2$ (Roberts and Garboczi [11] and Pabst and Gregorová [24] analyzed this special case, which corresponds to porous material with spherical pores and the matrix Poisson ratio is 0.2), the equation is deduced to a simple power-law relation, $E(P) = E(P_0)(1-P)^2$.

The more frequently used power-law relation is a semi-empirical equation proposed by Phani and Niyogi [16,29].

$$E(P) = E(P_0)\left(1 - \frac{P}{P_C}\right)^n \tag{5}$$

This equation is also the one that Zhang et al. [10] chose to consider the porosity-dependence of elastic modulus. The equation shows good agreement with the experimental results over a wide range of porosity and is approved by many researchers [10,11,30]. In addition, the equation allows for the possibility that elastic modulus reaches zero at a porosity lower than 100%, which conforms to most cases of practical interest that the elastic modulus reduces to zero already at such porosity [6,24]. Pabst et al. [6] and Pabst and Gregorová [12] summarized the existing elastic modulus-porosity relations, and retained important features of equations (4) and (5), then proposed a combined relation.

$$E(P) = E(P_0)(1 - [M]P + ([M]-1)P^2)\left(\frac{1 - P/P_C}{1-P}\right) \tag{6}$$

This relation inherits the advantages of the aforementioned equations. It can fully satisfy the boundary conditions, i.e., $E(P) = E(P_0)$, when $P = 0$, and $E(P) = 0$, when P approaches 1. And also allows the possibility of $E(P) = 0$, when $P = P_C$, inheriting from Phani–Niyogi equation. More importantly, it is also self-consistent and can deduce to many of the classical relations, e.g., Coble and Kingery relation [26], Phani and Niyogi relation [16,29], Hasselman relation [31], and Gibson and Ashby relation [32]. With those advantages, the model can well describe the porosity-dependent elastic modulus of lots of materials. Although this is also a semi-empirical relation, it is probably the most rational porosity-dependent elastic modulus model at ambient temperature for now.

2.2 Temperature-dependent elastic modulus model

The elastic modulus of porous metals with different porosities is extensively studied at ambient temperature. However, their temperature dependence does not gain as much attention as their porosity dependence, although the temperature-dependent elastic modulus is also a basic mechanical parameter for their high-temperature application [14,33]. Few researchers systematically studied the temperature-elastic modulus of porous metals in theory. Fortunately, there are some temperature-elastic modulus models that do not restrict their applications to specific materials. And the decoupling of temperature and porosity is reasonably based on the discussion in Section 2.1. Thus, these models can be used on porous metals.

One of the most frequently used temperature-dependent Young's modulus models is Wachtman et al.'s relation [34].

$$E(T) = E(T_0) - BT\exp(-T_D/T) \tag{7}$$

where $E(T_0)$ denotes the elastic modulus at room temperature. This model is also the one that Zhang et al. [10] chose in their model for considering the temperature-dependence of elastic modulus, and shows a good description of experimental data. To compensate for the deficiency that Wachtman's equation cannot describe more complicated changes in Young's modulus at a much higher temperature range, Li et al. [35] made a contribution to improving the Wachtman's equation.

$$\begin{aligned} E(T) = {} & E(T_0) - BT\exp(-T_m/T) \\ & + B_1(T - B_2T_m + |T - B_2T_m|)\exp(-T_m/T) \end{aligned} \tag{8}$$

where T_m denotes the melting point of materials, B_1 and B_2 are the material constants. Good agreement between the calculated results of the model and experimental data of HfB_2, $HfC_{0.67}$, and $HfC_{0.98}$ has been obtained at ultrahigh temperatures. After that, Zhang et al. [10] improved Wachtman's equation in another way. Considering that grain boundary sliding will have effects on Young's modulus at ultrahigh temperatures (Wachtman's equation ignored this), Zhang et al. also added an additional term based on Wachtman's equation, $B_1(T - T_S + |T - T_S|)\exp(-T_0/(T - T_S))$, where T_S denotes the temperature at which grain boundary sliding begins to have an influence on Young's modulus [10]. The model also shows good applicability at ultrahigh temperatures. Although the aforementioned works make great contributions to the characterization of temperature dependence of elastic modulus, their defects are also obvious, i.e., all of them are semi-empirical models. In spite of the good phenomenological description of the experimental data, their prediction values are very limited. In addition, determination of the many fitting parameters in the models is another trouble one has to tackle with when using them.

Recently, Li et al. [36] reviewed the temperature-dependent elastic modulus models and derived a new model without phenomenological fitting parameters:

$$E(T) = \frac{\left(1 + \int_0^{T_0} \alpha(t)\mathrm{d}t\right)^3}{\left(1 + \int_0^{T} \alpha(t)\mathrm{d}t\right)^3} \times \left(1 - \frac{\int_{T_0}^{T} C_V(t)\mathrm{d}t}{\int_{T_0}^{T_m} C_V(t)\mathrm{d}t + \Delta_{fus}H}\right)^{1/2} E(T_0) \quad (9)$$

where α denotes the linear expansion coefficient, C_v denotes the heat capacity at constant volume, T_0 denotes an arbitrary temperature, and $\Delta_{fus}H$ denotes the molar enthalpy of fusion at the melting point. The model is capable of predicting Young's modulus, elastic constant, and shear modulus at different temperatures, and has been validated by many kinds of dense metals. It can predict the elastic modulus well from extremely low temperature to almost the melting point of metallic materials, which are difficult to obtain through experiments, with reference to an easy-to-access elastic modulus. Compared with various other temperature-dependent elastic modulus models for metallic bulk materials, this model shows many advantages [36,37].

Given the above investigations, in this study, we will take Pabst's model and Li's model for $E(P)$ and $E(T)$ in equation (3), respectively, and deduce the following model:

$$E(T,P) = E(T_0,P_0)\frac{\left(1 + \int_0^{T_0} \alpha(t)\mathrm{d}t\right)^3}{\left(1 + \int_0^{T} \alpha(t)\mathrm{d}t\right)^3} \times \left(1 - \frac{\int_{T_0}^{T} C_V(t)\mathrm{d}t}{\int_{T_0}^{T_m} C_V(t)\mathrm{d}t + \Delta_{fus}H}\right)^{1/2} \times (1 - [M]P + ([M] - 1)P^2)\left(\frac{1 - P/P_C}{1 - P}\right) \quad (10)$$

Hence, a new temperature-porosity-dependent elastic modulus model is obtained. And all parameters in the relation have definite physical significance; thus, the model has predictive value on elastic modulus at different temperatures and porosities with reference to an easy-to-access elastic modulus.

3 Validation and discussion

In this part, the newly developed temperature-porosity-dependent elastic modulus model is validated by comparison between the experimental data and calculated results of the model. Unfortunately, as mentioned in Section 1, although the individual effects of temperature and porosity on elastic modulus are extensively studied, their simultaneous effects are rarely reported and immethodical. We made the greatest efforts, however, only the experimental data of elastic modulus of porous nickel (Ni) [38,39] and aluminum (Al) [40] were found, and comparison with them is made in this section.

In calculation, the temperature-dependent molar heat capacity at constant pressure (for solid materials, the difference between molar heat capacity at constant pressure and at constant volume is very small, thus, the molar heat capacity at constant pressure was used in the calculation) above room temperature of Ni and Al was obtained from the literature [41], with a multinomial expression of $C_P = a + b \times 10^{-3}T + c \times 10^5 T^{-2} + d \times 10^{-6}T^2$. The value of parameters in the expression in different temperature ranges is shown in Table 1. Their molar heat capacity at constant pressure at low temperatures was obtained from literature [42]. The melting point of Ni and Al are 1,726 and 933 K [43], respectively. And the enthalpy of fusion at the melting point of them are 17,472 and 10,719 J·mol^{-1} [43], respectively. The temperature-dependent linear thermal expansion coefficient of them was obtained from literature [42,44].

Parameters used in the calculation, i.e., the reference Young's modulus or shear modulus, intrinsic elastic modulus [M], and critical porosity P_C, are shown in Table 2. As can be seen from Figures 1–6, the comparisons between experimental and calculated Young's modulus or shear modulus of open cell porous Ni and open/closed cell

Table 1: Parameters in the multinomial expression of temperature dependent molar heat capacity at constant pressure of Ni and Al

Porous metal	*a*	*b*	*c*	*d*	Temperature range (K)
Ni	19.083	23.497	—	—	298.15–500
	−251.166	356.439	259.454	—	500–631
	467.194	−678.737	—	—	631–640
	−385.698	404.225	654.532	—	640–700
	−10.874	54.668	56.476	−16.489	700–1,400
	36.192	—	—	—	1,400–1,726
Al	31.376	−16.393	−3.607	20.753	298.15–933

Table 2: Parameters used in the calculation

Figure	Reference parameter			[*M*]	P_C
	Temperature	Porosity	Young's/Shear modulus (GPa)		
1	$T/T_m = 0.1$	$P = 0.961$	0.34	2	1
2	$T = 20$°C	0	213.12		
3	$T/T_m = 0.1$	$P = 0.961$	0.13		
4	$T = 330$°C	0	86.42		
5	$T = 21$°C	$P = 0.42$	45.78	1	
6	$T = 21$°C	$P = 0.42$	9.67		

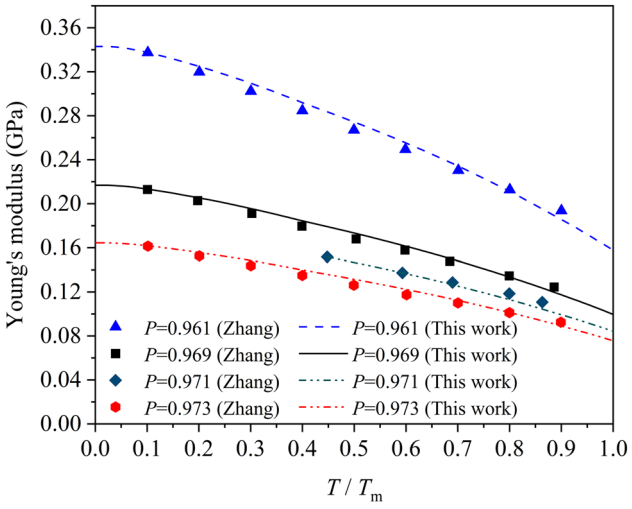

Figure 1: Comparison between experimental and calculated Young's modulus of open cell porous Ni at different temperatures with porosity $P = 0.961$, $P = 0.969$, $P = 0.971$, and $P = 0.973$, respectively.

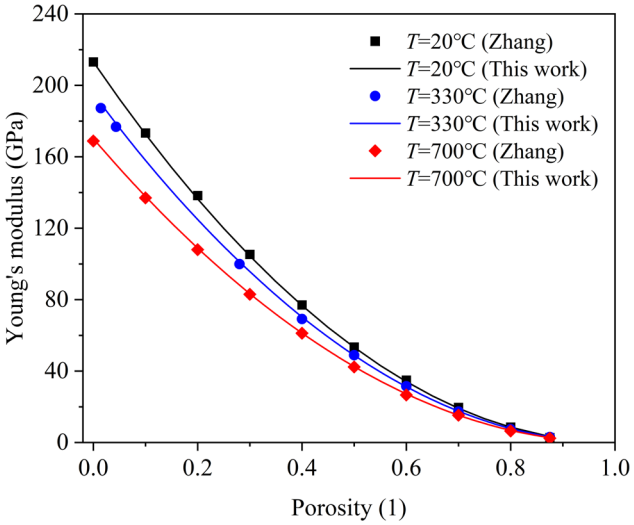

Figure 2: Comparison between experimental and calculated Young's modulus of open cell porous Ni at different porosities with temperatures $T = 20$°C, $T = 330$°C, and $T = 700$°C, respectively.

porous Al at different porosities and different temperatures, indicate that very good agreement has been obtained. It means the temperature-porosity-dependent elastic modulus model for metallic materials developed in this study has been validated.

Inheriting advantages from the temperature-dependent elastic modulus model established by Li et al. [36], the model developed in this study can predict elastic moduli at extremely high and low temperatures based on a reference elastic modulus. Since experiments at room temperature are easier to conduct than those at high and low temperatures, the elastic modulus at near room temperature can be chosen as the reference parameter preferentially (reference parameters used in the calculation in this article are shown in Table 2). Moreover, as can be seen in Figures 1 and 3, the model well predicts the elastic moduli of porous metallic materials from extremely low temperature to near melting point of Ni, which also indicates that the model is suitable for a very wide temperature range.

As for porosity dependence, as can be seen in Figures 2 and 4–6, comparisons between experimental and calculated Young's modulus and shear modulus of Ni and Al at different porosities with different temperatures indicate that good agreement has been obtained. More significantly, as shown in Figures 2 and 4, the good agreement is maintained from dense material to about 0.9 porosity, which is certainly a very wide porosity range. In calculation, the intrinsic elastic modulus [*M*] and

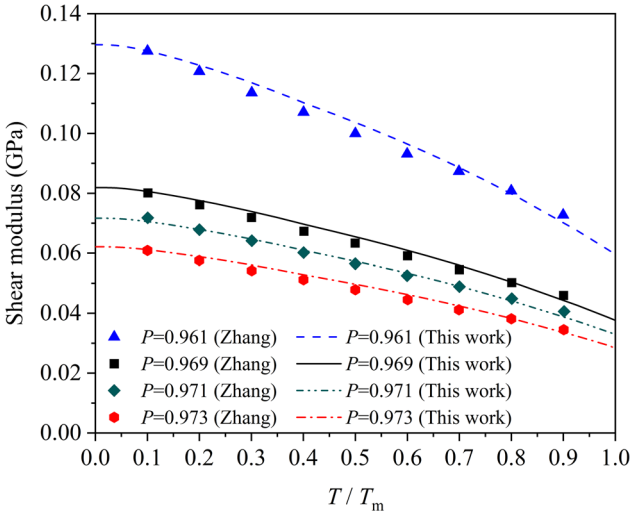

Figure 3: Comparison between experimental and calculated shear modulus of open cell porous Ni at different temperatures with porosity $P = 0.961$, $P = 0.969$, $P = 0.971$, and $P = 0.973$, respectively.

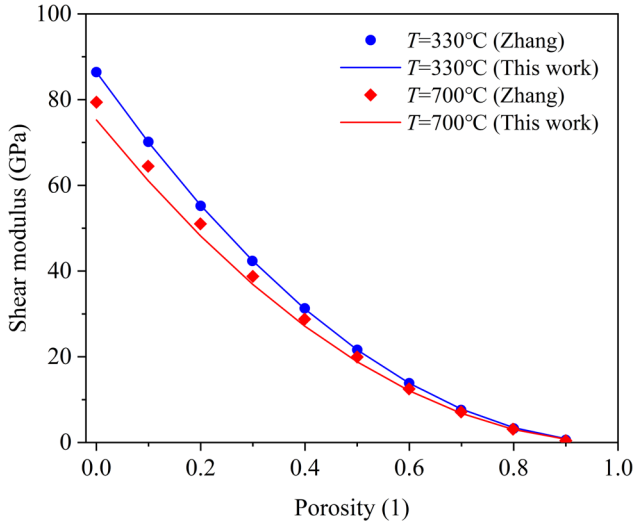

Figure 4: Comparison between experimental and calculated shear modulus of open cell porous Ni at different porosities with temperatures T = 330°C and T = 700°C.

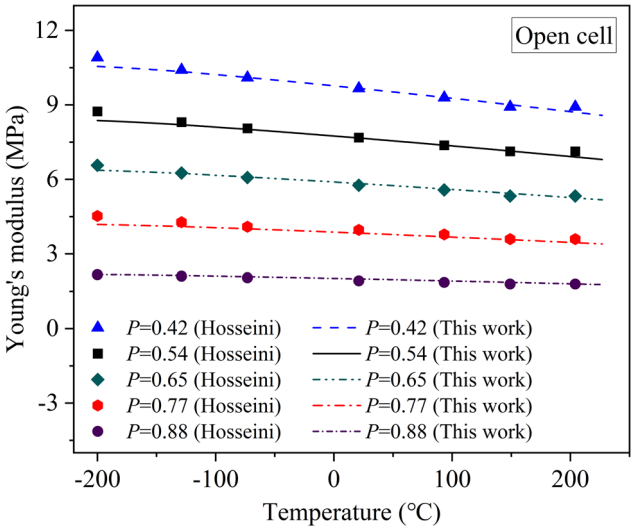

Figure 6: Comparison between experimental and calculated Young's modulus of open cell porous Al at different temperatures with porosity P = 0.42, P = 0.54, P = 0.65, P = 0.77, and P = 0.88, respectively.

critical porosity P_C for Al are both 1, and for Ni, they are chosen as 2 and 1, respectively. It should be noted that the coefficient in the classic Coble-Kingery relation have clear physical significance. Although the first order in the relation is determined only for dilute system of non-interacting spherical pores [24,26], the main purpose of the second order is tackling with the strong nonlinear porosity dependence of elastic modulus. Thus, the applicability of the relation has been extended to high porosity range. Moreover, the derivation of the coefficient is based on the premise of isotropy materials. Therefore, this should be adopted as the basic limitation for its application.

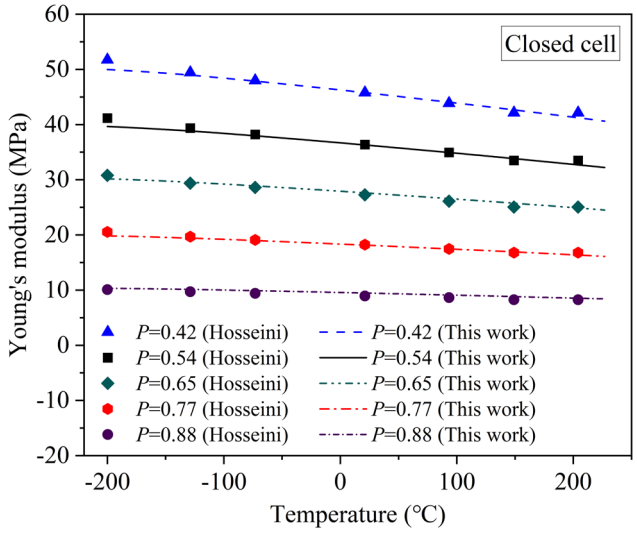

Figure 5: Comparison between experimental and calculated Young's modulus of closed cell porous Al at different temperatures with porosity P = 0.42, P = 0.54, P = 0.65, P = 0.77, and P = 0.88, respectively.

In addition, in a special case of $[M] = 2$ and $P_C = 1$ (when the spatial connectivity of studied porous metal is supposed to be sufficient to sustain an applied stress at super high porosity [8]), i.e., $E(P) = E(P_0)(1 - P)^2$, the same results of the relation and Gibson-Ashby model [32] can be found when fitting a large number of experimental results. And the latter is derived without the assumptions of spherical pore shape or non-interacting system. Therefore, in this case, it is not the spherical pores shape or connectedness of pores, but the approximate isometry is the decisive criterion of application conditions of the relation [6]. In this case, relation (10) has the form of

$$E(T,P) = E(T_0)\frac{\left(1+\int_0^{T_0}\alpha(t)\mathrm{d}t\right)^3}{\left(1+\int_0^{T}\alpha(t)\mathrm{d}t\right)^3} \times \left(1-\frac{\int_{T_0}^{T}C_V(t)\mathrm{d}t}{\int_{T_0}^{T_m}C_V(t)\mathrm{d}t+\Delta_{fus}H}\right)^{1/2}(1-P)^2 \quad (11)$$

which is a very simple and elegant relation considering the simultaneous dependence of elastic modulus on the variables of temperature T and porosity P. All parameters in the relation have definite physical significance and can be determined easily. Thus, the model has a predictive

value on the elastic modulus at different temperatures and porosities, with reference to an easy-to-access elastic modulus. Since the elastic modulus of dense material at room temperature is easier to obtain, it is suggested to be chosen as the reference parameter preferentially. It is worth noting that in the validation of relation (10), Young's/shear modulus at different temperatures and porosities is predicted with $[M] = 2$ and $P_C = 1$, as can be seen from Figures 1–4. Thus, it is actually a validation and classic application of model (11). Furthermore, according to the relationship between intrinsic elastic modulus and the Poisson ratio of matrix metal [6,25], the intrinsic Young's modulus of 2 or approximately 2 can be obtained when the matrix Poisson ratio is $0.1 < \nu < 0.4$. And the same results for intrinsic shear modulus can be obtained when $0.17 < \nu < 0.27$. Thus, the authors suggest that the application conditions of relation (11) are restricted to $0.1 < \nu < 0.4$ for Young's modulus and $0.17 < \nu < 0.27$ for shear modulus, which covers most of the metallic materials.

As aforementioned, all parameters in the relation (10) have definite physical significance. However, determination of the intrinsic elastic modulus $[M]$ and critical porosity P_C is sometimes a challenge in practice, especially for critical porosity, since it is a posteriori parameter for real materials due to the difficulties in assessing and quantifying the pore size distribution and connectivity. Considering this, some researchers, even including Pabst et al. themselves [6,12], tend to regard critical porosity P_C, and sometimes including the intrinsic elastic modulus $[M]$, as fitting parameter. In this way, relation (10) can be quite conveniently and universally used to provide highly effective descriptions of variation in elastic modulus with mean porosity and temperature. The calculated results in Figures 5 and 6 are typical applications of this condition. However, this advantage is obtained at the sacrifice of physical significance and predictive value of the relation. Since the intrinsic elastic modulus is a priori parameter, the authors suggest that one can retain the physical significance of it if Poisson ratio is obtained. However, as aforementioned, derivation of the intrinsic elastic modulus is based on the premise of isotropy materials, one has to pay attention to this application restriction in this condition. This seems to be a contradiction, and future efforts can be made to solve this problem.

4 Conclusion

In this study, the simultaneous and individual dependence of elastic modulus on temperature and porosity are analyzed, and relative theoretical models are reviewed. In this way, a new temperature-porosity-dependent elastic modulus model is developed, and all parameters in the relation have definite physical significance. Thereafter, the model is validated by comparisons between the experimental and calculated Young's modulus and shear modulus of open cell porous Ni and open/closed cell porous Al. And very good agreements, from extremely low to ultrahigh temperature, from dense material to about 0.9 porosity, have been obtained with reference to an easy-to-access elastic modulus. Since experiments on dense material at room temperature are easier to conduct, the elastic modulus at room temperature of dense material is suggested to be chosen as the reference parameter preferentially. The original model (relation (10)) is restrained to isotropy materials and the critical porosity is difficult to assess. However, when $[M] = 2$ and $P_C = 1$, a very simple and elegant relation can be obtained. This relation is absolutely a phenomenological parameter-free predictive one. It has the decisive criterion of pores approximate isometry, and $0.1 < \nu < 0.4$ for Young's modulus and $0.17 < \nu < 0.27$ for shear modulus, which covers most of the metallic porous materials. In addition, if the intrinsic elastic modulus $[M]$ and critical porosity P_C are regarded as fitting parameters, the relation can be quite conveniently and universally used to provide highly effective descriptions of variation in the elastic modulus with mean porosity and temperature.

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Conflict of interest: Authors state no conflict of interest.

Informed consent: Informed consent has been obtained from all individuals included in this study.

Data availability statement: The data used to support the findings of this study have not been made available because they also form part of an ongoing study.

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