



Optimization and modeling of sinter-brazing of porous copper-based composites joined to a wrought steel substrate

H. Ghazanfari^{1*}, H. Hassanzadeh²

¹Department of Mining, Metallurgical and Materials Engineering, Université Laval, Quebec, QC, Canada

²Department of Chemical Engineering, Université Laval, Quebec, QC, Canada

*Corresponding author e-mail address: hadi.ghazanfari.1@ulaval.ca

Abstract

Sinter-brazing of a powder-metallurgy porous copper-based composite to a wrought steel substrate was investigated. Two commercial Cu-based filler metals (Hi-Temp 548 disk and CDA 521) and different heating profiles were evaluated to identify a process window that maximizes joint performance while limiting wicking of the molten filler into the open porosity. Peak temperature (1010–1020 °C) and holding time (5–10 min) were varied under N₂. Shear testing and metallography show that increasing peak temperature or holding time reduces joint shear strength due to excessive infiltration of the filler and associated microstructural coarsening. The maximum joint shear strength (8.76 ± 0.5 MPa) was obtained using Hi-Temp 548 at 1015 °C with a 5 min hold. A three-dimensional CFD model based on the volume-of-fluid method and the continuum surface-force formulation was developed to predict filler infiltration into the porous compact. The predicted infiltration depth (415 μ m) agreed with experiments (389 μ m) within 7%. Parametric simulations indicate that infiltration increases with decreasing filler density and viscosity and with increasing holding time, with holding time being the dominant factor.

Keywords: Sinter-brazing, Powder metallurgy, Porous composites, Computational fluid dynamics

1. INTRODUCTION

Powder metallurgy (PM) enables near-net-shape manufacturing and compositional tailoring of copper-based composites and porous compacts, which is particularly valuable for functional materials such as friction components and thermal-management structures. In braking-relevant systems, Cu-based PM composites have been demonstrated as viable candidates for severe service conditions, including high-speed applications where both mechanical integrity and tribological stability are required [1]. However, many PM components must ultimately be integrated into multi-material assemblies (e.g., attaching a porous Cu-based compact or friction layer to a structural steel backing), and the intrinsic porosity of PM bodies complicates conventional joining approaches [2].

Sinter-brazing offers a manufacturing route in which sintering and brazing occur within a single thermal cycle, reducing processing steps and enabling formation of complex assemblies with fewer reheating-induced distortions. Recent work on friction-material/backing-plate systems shows that sinter-brazing can create defect-free metallurgical interfaces and measurable joint shear strength, highlighting its potential for high-temperature braking assemblies [3]. From a processing perspective, sinter-brazing follows the fundamentals of brazing (surface preparation, wetting, and capillary gap

filling) while being executed concurrently with powder sintering, which makes process control more sensitive than in conventional, two-step routes [4].

A defining challenge in sinter-brazing porous PM parts is capillary-driven wicking of molten filler into the interconnected pore network, which can deplete filler from the joint plane and compromise bond formation [4, 5]. The governing physics is closely related to capillary infiltration: classical Lucas–Washburn theory links penetration kinetics to pore size, liquid viscosity, surface tension, and wetting angle [6, 7]. Experimental brazing studies on porous copper systems corroborate the practical consequences of such filler redistribution; for example, seam thickness and interfacial integrity depend strongly on brazing temperature/time due to diffusion and melt redistribution into/along porous features [8, 9]. Controlling the competition between braze-gap capillarity and pore-network capillarity is therefore critical.

Increasing compact density (reducing connected porosity and effective pore size), selecting appropriate joint clearance, and controlling furnace atmosphere/oxide reduction conditions are repeatedly identified as practical levers that directly affect wetting and wicking tendencies [4]. Complementary work on porous copper joining further indicates that alternative heating/filler-feeding approaches and careful control of the thermal cycle can modify interfacial microstructures and improve bonding outcomes in porous substrates [10]. Since filler infiltration is strongly influenced by liquid properties and thermal-cycle parameters, understanding their effect is essential for maintaining sufficient filler within the joint while limiting excessive wicking into the porous compact. This motivates the combined experimental and numerical approach adopted in the present study.

While experiments remain essential, process optimization is accelerated by predictive modeling that resolves coupled free-surface motion and capillary/viscous flow—especially when infiltration inside a porous network cannot be directly observed. Interface-capturing Computational Fluid Dynamics (CFD) methods such as Volume-of-Fluid (VOF) [11] combined with Continuum Surface Force (CSF) surface-tension modeling [12] provide a practical framework for capillary-dominated molten-metal infiltration problems, and recent validated infiltration simulations demonstrate the feasibility of quantitative prediction when models are benchmarked against experiments [13, 14]. In this work, we (i) experimentally establish a sinter-brazing processing window for joining porous Cu-based PM compacts to a wrought steel substrate using two commercial Cu-based filler metals while limiting detrimental wicking, and (ii) develop and validate a 3D CFD/VOF model that predicts infiltration depth and supports parametric assessment of filler properties (e.g., density and viscosity) and thermal-cycle variables.

The remainder of this paper is organized as follows. Section 2. describes the materials, sinter-brazing procedures, and characterization methods, and presents the numerical framework used to model molten-filler infiltration. Section 3. details the governing equations and the VOF-based formulation adopted in the simulations. Section 4. presents the experimental results and discusses the effects of processing parameters on joint performance, followed by validation of the numerical model and a parametric analysis of infiltration.

2. MATERIALS AND METHODS

In this section, the experimental procedures used to manufacture and sinter-braze the porous copper-based compacts to the steel substrate are described, together with the characterization methods employed to quantify joint performance and microstructural evolution. In addition, the numerical framework developed to model molten-filler infiltration during sinter-brazing is presented, including the computational domain, governing equations, and implementation details.

2.1 Experiments

Commercial water-atomized powders of Cu (99.5% purity, 48–75 μm), graphite (96% purity), and CrFe compound (95% purity, < 75 μm) were used as raw materials. The powder mixture was blended in a V-shaped mixer for 2 h and cold-pressed at 500 MPa in a steel die to a green density of 5.3 g cm³. The compacts were then placed in a sintering tube furnace for sinter brazing following different temperature profiles. All sinter-brazing experiments were carried out in a N₂ atmosphere with a dew point lower than −40 °C. Figure 1 shows the set-up for the sinter-brazing test.

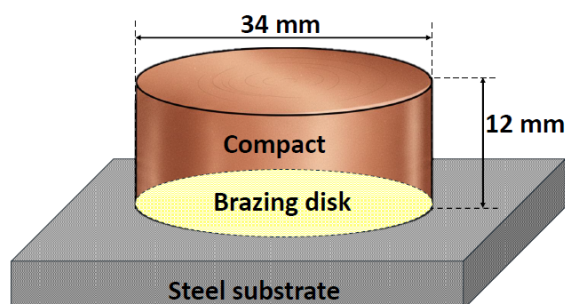


Fig. 1. Schematic of the sinter-brazing test specimen assembly. A cylindrical powder compact (34 mm diameter and 12 mm height) is placed on a steel substrate prior to sinter brazing; the main dimensions are indicated.

Tab. 1. Chemical composition of the brazing materials (Hi-Temp 548).

Element	Cu	Zn	Ni	Mn	Si	Other
wt. %	55	balance	6	4	0.1-0.4	0.15

Tab. 2. Chemical composition of the brazing materials (CDA 521).

Element	Cu	Sn	P
wt. %	balance	8	0.32

Tab. 3. The physical properties of Hi-Temp 548 brazing material at 1015 °C.

Parameters	Symbol	Value	Units
Density	ρ	7303	kg/m ³
Viscosity	μ	0.0036	kg/(m.s)
Solidus temperature		820	°C
Liquidus temperature		920	°C

The samples were heated to the peak temperature (1010 °C, 1015 °C, and 1020 °C) at a heating rate of 10 °Cmin⁻¹ and held at the peak temperature for different durations (5 min and 10 min), followed by cooling at 5 °Cmin⁻¹ down to 980 °C. The samples were then air-cooled from 980 °C to room temperature. CDA 521 and Hi-Temp 548 brazing materials were selected in this study due to their high operating temperature. The latter was supplied as disks with a diameter of 34 mm with a thickness of 0.2 mm. The chemical compositions of the brazing materials are given in Table 1 and Table 2. The physical properties of Hi-Temp 548 and CDA 521 are presented in Table 3 and Table 4.

Tab. 4. The physical properties of CDA 521 brazing material at 1015 °C.

Parameters	Symbol	Value	Units
Density	ρ	8400	kg/m ³
Viscosity	μ	0.0039	kg/(m.s)
Solidus temperature		882	°C
Liquidus temperature		1027	°C

Microstructural characterization of the sinter-brazed specimens was carried out by cross-sectioning the samples using a cut-off saw. The cross-sections were then mounted in resin and polished using conventional metallographic preparation procedures for optical microscopy. The samples were etched with 1% Nital to better reveal the microstructure. The mechanical properties of the sinter-brazed joints were characterized using Brinell hardness testing and shear testing. The Brinell hardness measurements were performed within the bulk porous composite material. Five indentations were performed for each specimen and the reported hardness values represent the mean $\pm$ standard deviation. Figure 2 presents a schematic of the shear test. The shear strength of the compacts and joints was measured using a universal testing machine (Instron 3369) at a crosshead displacement rate of 1 mm.min⁻¹. All tests were performed at ambient temperature. For each processing condition, three independent specimens were tested, and the reported shear strengths are presented as the mean value $\pm$ standard deviation. Brinell hardness measurements were conducted using a standard 10 mm diameter tungsten carbide ball indenter, under a load of 500 kgf and a dwell time of 30 s.

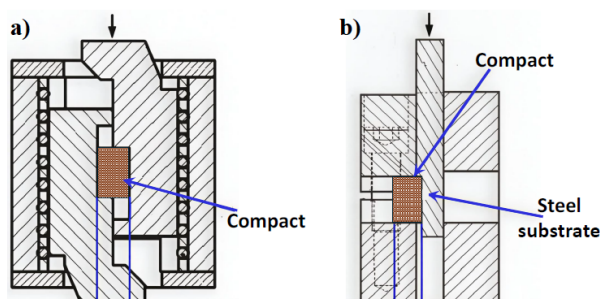


Fig. 2. Schematic illustration of the shear test used to evaluate the shear strength of sinterbrazed specimens: (a) compact specimen and (b) brazed joint specimen (compact/steel substrate). The applied load (arrows) is transferred through the fixture to promote interfacial shear at the joint plane. Reproduced from [15] with permission from Elsevier. © 2018 Elsevier Ltd .

2.2 Simulations

A three-dimensional numerical modeling tool using a CFD approach was developed to study the flow behavior of the brazing materials during sinter brazing. The multiphase flow model was employed to simulate the brazing process. The volume of fluid (VOF) method was used to trace the free surfaces of the multiphase system. Gravity force, buoyancy force, and Marangoni convection were considered in the model. The accuracy of the numerical simulation was verified with experimental data. After verification, sets of numerical simulations were conducted to study the effect of density and viscosity of the brazing material on the infiltration depth of the brazing material.

3. GOVERNING EQUATIONS

In this section, a mathematical description of the model and the governing equations used to investigate fluid flow within a porous medium are provided. For the simulation of multiphase flow in which capillary and viscous forces dominate, a set of partial differential equations (PDEs) is solved for the mixture rather than separately for each phase. Accordingly, the continuity and momentum equations are solved simultaneously, and a single velocity and pressure field is obtained for the multiphase system. The mixture continuity and momentum equations are written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho u \otimes u) = -\nabla p + \nabla \cdot [\mu (\nabla u + \nabla u^T)] + F_s + \rho g, \quad (2)$$

where u is the velocity vector, p is pressure, ρ and μ are the (mixture) density and viscosity, respectively, F_s is the capillary (surface-tension) force, and g is the gravitational acceleration.

3.1 Volume-of-fluid (VOF) method

The volume-of-fluid (VOF) method was used to track the phase volume fraction in the computational domain [11]. The VOF approach is suitable for unsteady, immiscible two-phase displacements in which the phases do not interpenetrate. In this method, a transport equation is solved for the volume fraction of one phase, and the volume fraction of the other phase follows from $\alpha_1 + \alpha_2 = 1$.

The VOF volume-fraction transport equation is

$$\frac{\partial \alpha_1}{\partial t} + u \cdot \nabla \alpha_1 = 0, \quad (3)$$

where α_1 is the volume fraction of phase 1 and u is the bulk (mixture) velocity. The mixture properties are computed using volume-fraction-weighted averages:

$$\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2, \mu = \alpha_1 \mu_1 + \alpha_2 \mu_2, \alpha_1 + \alpha_2 = 1. \quad (4)$$

The resulting ρ and μ are then used in Eqs. (1)–(2).

Surface tension becomes important when capillary forces dominate viscous forces. In this study, the continuum surface force (CSF) formulation was used to model

surface tension by introducing a volumetric source term in the momentum equation. The surface-tension force is written as

$$F_s = \sigma \kappa \delta(x - x_{int}) n, \quad (5)$$

where σ is the surface-tension coefficient, $\delta(\cdot)$ is a Dirac delta function concentrated at the interface location x_{int} , n is the unit normal vector at the interface, and κ is the curvature. The unit normal and curvature are defined by

$$n = \frac{\nabla \alpha_1}{|\nabla \alpha_1|}, \quad (6)$$

$$\kappa = \nabla \cdot n. \quad (7)$$

The preprocessor GAMBIT 2.4.6 [16] was used to set the geometry, the mesh, and the boundary conditions of a 3D domain. The solver and postprocessor ANSYS FLUENT 18.2 [17] were used to solve the equations by finite volume discretization. As shown in Fig. 3, a uniform structured mesh composed of 1,548,000 cells was used for simulation. A coarser mesh resulted in incorrect results. However, using a finer mesh significantly increased computational time without noticeably improving simulation results.

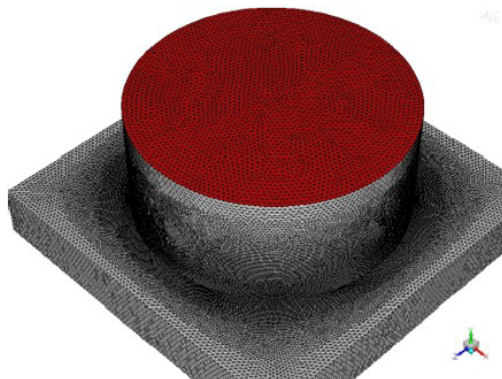


Fig. 3. Computational domain and mesh used in the 3D simulations. The grid consists of 1,548,000 hexahedral cells, generated in GAMBIT 2.4.6 and solved using the finite-volume method.

4. RESULTS AND DISCUSSION

Table 5 summarizes the mechanical properties of the sinter-brazed joints and compacts. Within the investigated process window, sinter-brazing at a peak temperature of 1015 °C for 5 min yielded the highest shear strength for both the joint and the compact. Increasing the peak temperature above 1015 °C reduced the joint shear strength, which is attributed to excessive infiltration (wicking) of the molten brazing material into the interconnected porosity of the sintered compact. In addition, higher temperatures promoted grain growth in the compact microstructure, which contributed to the reduction of compact shear strength. Similarly, increasing the holding time beyond 5 min increased the level of infiltration and reduced the joint shear strength. These interpretations are further supported

by the numerical simulation results (presented later), which demonstrates the influence of brazing temperature, holding time, density, and viscosity on infiltration depth. These simulation results are consistent with the experimental observations and provide additional support for the proposed interpretation of the observed changes in joint shear strength.

Sample 1, produced using the standard two-step route (sintering followed by brazing), exhibited relatively high joint shear strength despite the extended exposure to high temperatures. This behavior can be rationalized by noting that sintering prior to brazing may partially block the interconnected pores and reduce the subsequent infiltration during brazing. The compact shear strength for Sample 1 was lower than the sinter-brazed samples, most likely due to grain growth associated with two thermal cycles. Overall, the highest shear strength for both joint and compact was obtained using the Hi-Temp 548 disk at 1015 °C with a 5 min hold.

The CDA 521 filler was not suitable under the present conditions, as the compact was easily torn from the steel backing. This may be related to the higher liquidus temperature of CDA 521 compared to Hi-Temp 548; if the sinter-brazing temperature remains below the liquidus, the reduced flowability can degrade joint formation. Increasing the sinter-brazing temperature to compensate is not desirable because it would further promote grain growth and infiltration.

Tab. 5. Mechanical properties of the sinter-brazed parts compared with the standard two-step route (sintering followed by brazing). Reported values include shear strength of the joint and the porous compact, together with Brinell hardness (HB), for different filler metals and sinter-brazing thermal cycles.

Sample	Disk	Sinter-brazing temperature [°C]	Sinter-brazing holding time [min]	Shear strength Joint [MPa]	Shear strength Compact [MPa]	Hardness [HB]
1	Hi Temp 548–Standard (Sintering + Brazing)	970, 1020	-	8.72	7.52	19.7
2	CDA 541	1010	5	5.64 ± 0.5	8.06 ± 0.4	20.4 ± 2
3	Hi-Temp 548	1010	5	3.13 ± 0.3	8.11 ± 0.5	20.4 ± 2
4	Hi-Temp 548	1015	5	8.76 ± 0.5	8.33 ± 0.4	21 ± 2
5	Hi-Temp 548	1020	5	4.61 ± 0.3	7.51 ± 0.4	19.8 ± 2
6	Hi-Temp 548	1015	10	3.25 ± 0.2	7.41 ± 0.3	19.5 ± 2

Figure 4 shows the effect of sinter-brazing time and temperature on the microstructure of the compacts. The mean grain size was measured by averaging 50 grains at different locations using an image-analysis routine (ImageJ). The average grain size of Sample 1 was $30 \pm 2 \mu\text{m}$. The grain sizes of Samples 2 and 3 were similar because both samples were sinter-brazed at the same temperature, with an average grain size of $14 \pm 1 \mu\text{m}$, which is significantly smaller than Sample 1. Increasing the sinter-brazing temperature increased the mean grain size to $18 \pm 2 \mu\text{m}$ and $22 \pm 2 \mu\text{m}$ for Samples 4 and 5, respectively.

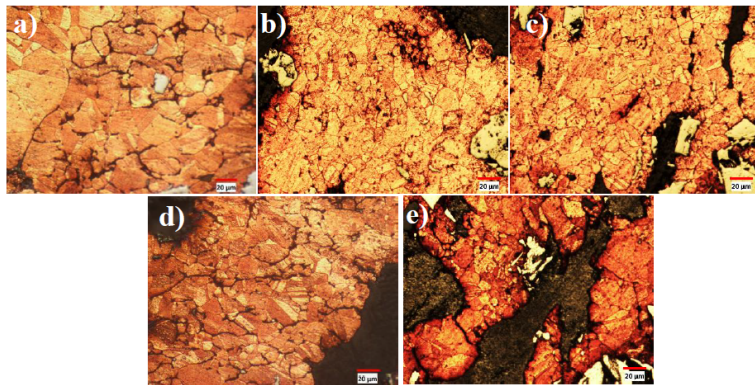


Fig. 4. Microstructure of the porous copper-based compact after sinter-brazing under different processing conditions: (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4, and (e) Sample 5. All images are shown at the same magnification (scale bar: 20 μm).

4.1 Model verification

To verify the simulation, the experimental findings were compared with numerical results. Figure 5 shows the liquid volume-fraction distribution at a holding time of 5 min after sinter-brazing at a peak temperature of 1015 °C. Figure 6 compares the infiltration depth obtained experimentally and numerically. The experimentally measured infiltration depth was 389 μm , which is slightly lower (7%) than the numerical prediction (415 μm). Overall, the agreement is acceptable. The difference between the experimental and numerical results may be attributed to idealizations in the numerical model. The present model assumes isothermal liquid flow and does not account for solidification, phase transformations, or evolving pore morphology during infiltration. These effects may influence the final infiltration depth and will be considered in future model developments.

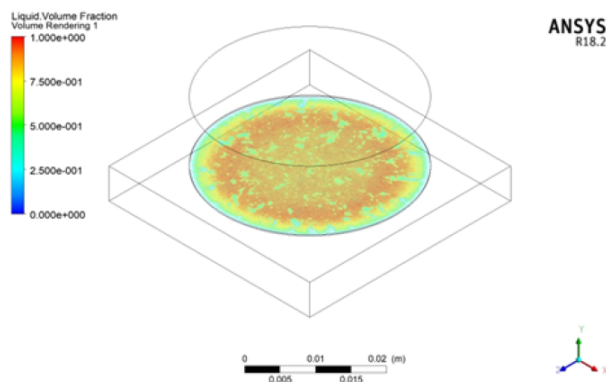


Fig. 5. Liquid volume-fraction distribution at the holding time of 5 min after sinter-brazing at the peak temperature of 1015 °C. This highlights the spatial distribution of molten filler within the porous compact and the remaining liquid in the joint region.

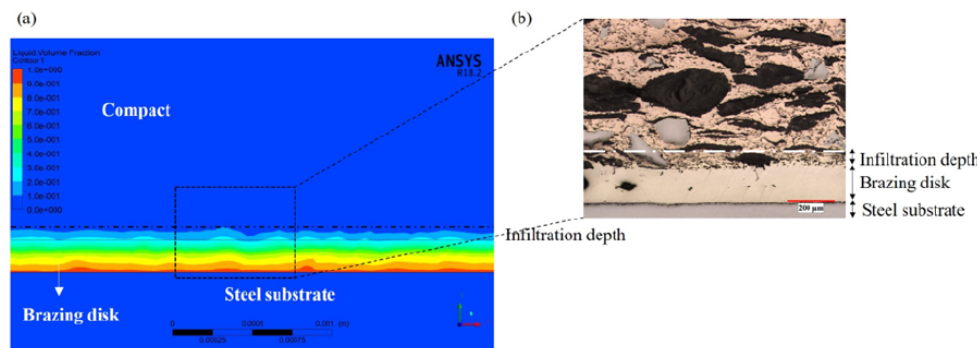


Fig. 6. Infiltration of brazing material (Hi-Temp 548) at a holding time of 5 min after sinter-brazing: (a) numerical simulation result and (b) experimental result.

4.2 Effect of density on the infiltration depth

Additional simulations were performed to investigate the effect of the brazing material density on the infiltration depth at a fixed viscosity $\eta = 0.0036 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ and a holding time of 5 min. As shown in Figure 7, the volume fraction of brazing material remaining at the joint is lower for a density of 4800 kg/m^3 than for Hi-Temp 548 (7300 kg/m^3), due to increased infiltration. Overall, increasing density decreases infiltration depth.

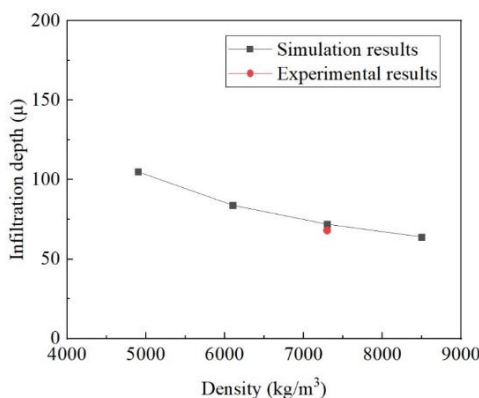


Fig. 7. Effect of brazing-material density on the infiltration depth. Red circle denotes experimental measurements and the black solid line denotes simulation predictions (holding time: 5 min; other properties held constant).

4.3 Effect of viscosity on the infiltration depth

Figure 8 shows the effect of viscosity on the infiltration depth at a density of 7300 kg/m^3 and a holding time of 5 min. Increasing viscosity decreases the infiltration depth. These results suggest that using a brazing material with higher density and viscosity can help mitigate excessive infiltration and preserve sufficient liquid in the braze gap for joint formation.

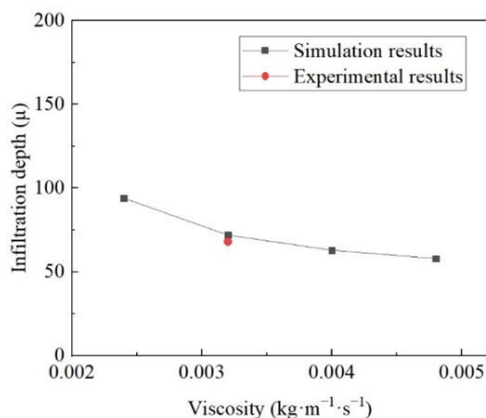


Fig. 8. Infiltration depth as a function of brazing-material viscosity. Red circle: experiment; black solid line: simulations (5 min hold; other properties fixed).

4.4 Effect of holding time on the infiltration depth

Figure 9 shows the effect of holding time on the infiltration depth. The infiltration depth increases significantly with holding time. Based on these results, holding time at the peak temperature is one of the most important parameters influencing the infiltration depth of brazing material during sinter-brazing.

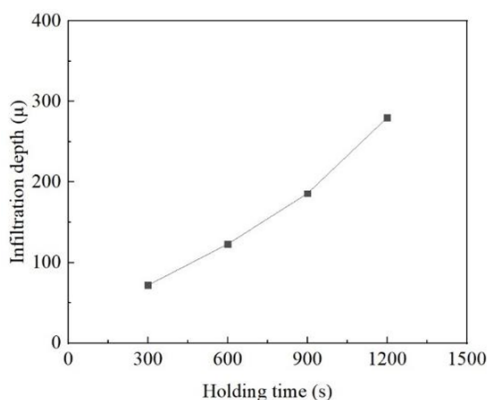


Fig. 9. Effect of holding time on the infiltration depth predicted by the simulations.

5. CONCLUSIONS

Porous copper-based PM compacts were successfully joined to a wrought steel substrate by sinter-brazing using Hi-Temp 548 disks as the filler metal. The optimal condition within the investigated window was a peak temperature of 1015 °C with a 5 min hold, which produced the highest joint shear strength (8.76 ± 0.5 MPa) while limiting excessive infiltration. A three-dimensional CFD/VOF model was developed to simulate molten filler infiltration into the porous compact and was validated against measured infiltration depth (389 μm experimentally versus 415 μm numerically, 7% difference). Parametric simulations show that infiltration increases as filler density and viscosity decrease and as holding time increases; among these, holding time exerted the strongest influence. These findings provide quantitative guidance for selecting filler properties and

thermal cycles to balance braze-gap filling and controlled infiltration in sinter-brazed porous copper/steel joints.

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