INTERNATIONAL JOURNAL OF MECHANICS
DOI: 10.46300/9104.2023.17.1 Volume 17, 2023

CFD investigation of the soldering process for a small spherical PCM made of lead-tin alloy

Mustafa Sabeeh Abood[1], Ammar Ghany[2]
[1]University of Baghdad, Baghdad Aljaderiah, Iraq
[2] University of Technology, Baghdad Aljaderiah, Iraq

Received: May 22, 2022. Revised: January 5, 2023. Accepted: February 11, 2023. Published: March 3, 2023.

Abstract— Unlike welding, soldering does not involve melting the work pieces. Soldering is a process in which two or more items are joined together by melting and putting a filler metal (solder) into the joint. Failure in the solder joint may make the system components lose their functions. Electrical wiring and electronic components are joined to devices and printed circuit boards using soldering. Soldering and brazing are both used in the assembly of musical instruments. Lead-tin alloy solder employed in the current investigation which has a diameter of 4 mm and a density of 11.0103 kg/m3 with continuous heat flux heating from the domain's left side and complete insulation on the other side. The melting of PCM was simulated using the ANSYS (Fluent) melting model. Three procedures were followed during the heating stage of the reflow process to perform the melting heat-transfer analysis. The simulation's results were recorded at regular intervals of 15 seconds. The results show melting rate increases as time proceeds. It is almost the same at the initial stages and increases in the middle and the end of the melting process. Heat transfer happens mostly through conduction during the first 0–30 seconds of the melting process, changing to natural convection as the material continues to heat up.

Keywords— heat transfer, PCM, Lead-tin alloy, Soldering Processes, CFD Simulation, Melting and solidification.

I. INTRODUCTION

SOLDERING is a process in which two or more items are joined together by melting and putting a filler metal (solder) into the joint, the filler metal having a lower melting point than the adjoining metal. Unlike welding, soldering does not involve melting the work pieces. In the past, nearly all soldiers contained lead, but environmental and health concerns have increasingly dictated the use of lead-free alloys for electronics and plumbing purposes [21].

Solder alloy is largely utilized in soldering as the adhesive substance to produce joins. To fix electronic components and/or create interconnections, it is intended to attach components like chips and/or chip modules with substrates. The entire piece of equipment ceases to work if even one joint or component is defective. As a result, the solder junction has a big impact on how well the system works [21].

When a solder junction is created, the solder paste, which is composed of fluxes, flux powders, solvent, and heat, is first forced to flow before being heated, melted, and resolidified [16].

The quality of the solder connection can be affected by a variety of variables, including coated metallization layer, reflow temperature, and solder paste quality (including solder powder and fluxes). The system components may not function anymore if the solder junction fails.[16]

A. Phase Change Materials (PCMs)

The materials utilized to store latent heat energy are known as PCMs. When heat energy is applied to or removed from certain materials, they transform from one state to another [17].

At constant temperature, they can transform from a solid to a liquid by absorbing latent heat of fusion and back again, or from a liquid to a gaseous state by absorbing latent heat of vaporization and back again, or from a solid to a gaseous state by absorbing latent heat of sublimation and back again. The most popular method for LHS is the phase transition from solid to liquid [20]. Figure 1 illustrates the phase change phenomena for the solid to liquid phase change mode. The shaded area displays the total heat energy stored during a material's transition from solid to liquid phase. The sum of sensible heat in the solid state, latent heat during phase change at a constant temperature, and sensible heat in the liquid state make up the total energy stored [25].

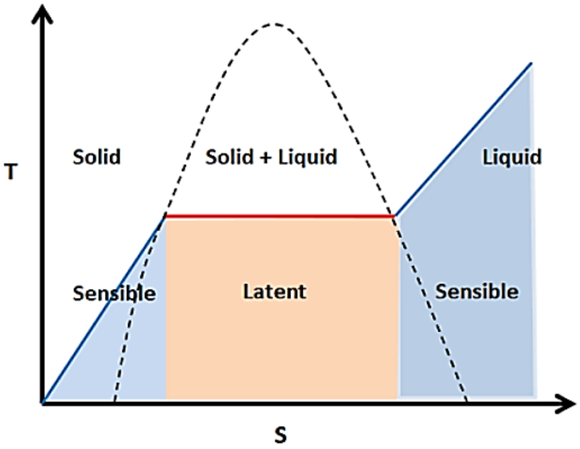


Fig. 1 Heat Stored during phase change of material

B. Applications

Plumbing, electronics, and metalwork, including jewelry and musical instruments, all involve soldering. Between copper pipes in plumbing systems, as well as joints in sheet metal objects like food cans, roof flashing, rain gutters, and car radiators, soldering creates somewhat permanent yet reversible connections.

The higher temperature silver soldering method is frequently used to manufacture and repair parts for jewelry, machinery, and some refrigeration and plumbing systems. Small mechanical components are frequently brazed or soldered as well. In stained glass work, lead came and copper foil are also joined via soldering.

Electrical wiring and electronic components are joined to devices and printed circuit boards using electronic soldering. With a soldering iron, electronic connections can be manually soldered. Many joints on a complicated circuit board can be made using automated techniques like wave soldering or the use of ovens, significantly lowering the cost of producing electrical products.

Soldering and brazing are both used in the assembly of musical instruments, particularly brass and woodwind instruments. Keywork and bracing are often brazed whereas brass bodies are frequently soldered together.

C. Solder

For various uses, soldering filler materials come in a wide range of alloys. The eutectic alloy containing 63% tin and 37% lead (also known as 60/40, which has a melting point nearly identical to that of 60/40) has traditionally been used in electronics construction. Plumbing, mechanical assembly, and other uses call for the usage of different alloys. Lead-silver for strength at temperatures above room temperature, cadmium-silver for strength at high temperatures, zinc-aluminum for aluminum and corrosion resistance, and tin-silver and tin-bismuth for electronics are a few examples of soft-solder.

A eutectic formulation provides advantages when used for soldering because it has the lowest melting point possible and the liquidus and solidus temperatures are the same, reducing the risk of a plastic phase. The least amount of heat stress is placed on electronic components when soldering by having the lowest melting point feasible. Additionally, the absence of a plastic phase enables faster wetting as the solder heats up and quicker setup as the solder cools. As the temperature falls through the liquidus and solidus temperatures, a non-eutectic formulation must stay stable. Any movement during the plastic phase could cause cracks, which would lead to an unstable joint.

The following is a list of typical tin- and lead-based solder compositions. The fraction shows a percentage of tin followed by lead, making a total of 100%:

- 63/37: melts at 183 °C (The only combination that melts at a single point rather than across a wide range is eutectic.)
- 60/40: melts between 183–190 °C
- 50/50: melts between 183–215 °C

Lead-free soldiers are being used increasingly often due to environmental concerns and the adoption of laws like the European RoHS (Restriction of Hazardous Substances Directive). They are also recommended for outdoor usage where rain and other precipitation may wash the lead into the groundwater or anyplace young children may come into touch with them (because they tend to put items in their mouths). Unfortunately, the majority of lead-free solders are not eutectic formulations and melt at a temperature of about 250 °C, which makes it more challenging to produce strong junctions with them.

Other common solders include high-temperature formulations (typically containing silver), which are used for high-temperature operation or for the initial assembly of items that must not become unsoldered during subsequent operations, and low-temperature formulations (often containing bismuth), which are frequently used to join previously-soldered assemblies without unsoldering earlier connections. Silver's melting temperature, adhesion and wetting properties, and tensile strength are all changed by alloying with other metals. Silver solders are the strongest and have the widest range of uses of all the brazing alloys [21]. There are specialty alloys with qualities including increased strength, the capacity to solder aluminum, improved electrical conductivity, and increased corrosion resistance [9].

The lead-tin alloy solder employed in the current investigation has a diameter of 4.115 mm. The mass of the solder connection is 0.05682 g, where the density of the alloy in the solder joint is 11.0103 kg/m3. The latent heat to be extracted from each solder joint is 1.4187 J [23], with the latent heat of the solder alloy being 2.4971104 J/kg.

Table 1. Thermal and physical properties used in the numerical analysis

95pb-5Sn Alloy
Liquidus Temperature 312^{o} C

Solidus Temperature 305^{o} C
Density: 11.0×10^{3} kg/m^{3}
Latent Heat: 2.4971×10^{4} j/Kg

Thermal Conductivity Temperature, K	Thermal conductivity, W/mK
$T\leq100$	35.098
$100< T \leq200$	33.7
$200< T \leq250$	30.13
$250< T \leq300$	25.38
$300< T \leq400$	19.443
Specific Heat Temperature,° C	Specific heat, kJ/kg K
$T\leq25$	0.1334
$25< T \leq127$	0.1376
$127< T \leq227$	0.1432
$227< T \leq327$	0.1478
$327< T \leq427$	0.1520

D. Soldering heat-transfer analysis objectives

Thermal fatigue is one of the primary reasons solder joints fail. Due to the internal stress concentration in the solder/dice and solder/slug interfaces, intermetallic compounds are typical what causes thermal fatigue to begin. Intermetallic compounds are created when Cu from the lead frame and/or Ni from the metallization layer diffuse to the solder junction and combine with Sn in the solder to generate new compounds. When the contact is exposed to greater temperatures for a longer length of time, the intermetallic compound issue becomes worse. Shrinkage porosity is the other significant flaw that is at fault. The solder alloy shrinks as it solidifies, as is well known. Therefore, the remaining liquid region of the solder will flow to feed the shrinkage after the initial part of the solder hardens. Therefore, it is easy to imagine that a shrinkage hole will occur in the final location to solidify, which is typically in the solder joint's center. The shrinkage porosity, which might have a large hole in the center depending on the cooling rate, temperature gradient, and feeding characteristics, is extremely harmful to the solder junction. Or, it can be acceptable to have somewhat minor shrinkage porosity that is equally distributed throughout the solder. It is therefore highly desirable to use a mathematical model to simulate the melting phenomena of the solder joint and evaluate the contours of liquid fraction, velocity, and temperature of particles of PCM at circular PCMs are the materials which are used for storing latent heat intervals are represented for a total melting time of energy. Experimental measurements in PCM (solder) joints are extremely difficult and expensive. The contours help to identify how the melting interface changes in form and motion as melting time increases. It is also described how the melting fraction changes over time and how this changes our understanding of the amount of melted PCM at various points in time.

There is evidence that soldering was used in Mesopotamia 5,000 years ago [2] It is believed that soldering first appeared extremely early in the history of metalworking, most likely before 4000 BC. [1] Hard soldering was used in the assembly of Sumerian swords from around 3000 BC. In the past, soldering was used to create tools, cooking utensils, jewelry, and other products. It was also used to assemble stained glass, among other things.

[5] investigated how to solder junctions are formed. [13] examined the joint's dimensions and form.[8] made an effort to forecast the solder junctions' performance life. In addition to attempting to estimate the life of the joints, [18] looked into the microstructure of the joints. The potential causes of creep have been researched by [16]. The stress cracking issue of joints under temperature cycling was taken into consideration by [19]. However, according to [23], this literature focuses mostly on problems with solder junctions that have a ball form. [24] examined the issue of thermal fatigue fracture for plate form solder junctions. [23] used an auto-rectifier to conduct a solidification heat-transfer analysis to determine how the temperature of the lead-tin alloy and the whole electronic component varied during the reflow process.

[14] investigated melting and freezing processes in phase change material storage using numerical and experimental methods. With and without heat transfer enhancement structures, they created a collection of experimental PCM storages. They compared the experimental results with the numerical predictions generated by the simulation program FEMLAB. The temperature distribution of the storage during the melting and freezing processes was well estimated using numerical techniques. To simulate the solidification of lead-free solder interconnections of a chip-scale packed component during reflow soldering, two thermal models at different levels, a component model and an interconnection model, were constructed [6]. Thermodynamic simulations related to the phase transitions occurring during melting and solidification were used to obtain the thermal characteristics of the connections. The model has been further extended by several additional research teams [11] and [12]. Additionally, a computational fluid dynamic (CFD) model has been developed to simulate the flow field within a conventional reflow oven [6]. It is likely due to the complexity of interconnection level modeling that a thorough three-dimensional thermal simulation at the component or interconnection level has not yet been given. On the one hand, the solidification of solder is heavily dependent on the time-dependent temperature distribution inside interconnections, which is an essential property. The distribution of temperature is affected by the thermal impact that solidification itself brings. To analyze the solidification of interconnections, thermal modeling must be integrated with thermodynamic and kinetic factors. Theoretical simulations have a difficult time with this.

II. MATHEMATICAL MODELING

Modeling and simulation of the melting of PCM were done using the ANSYS (Fluent) 2020 R2 melting model. This approach does not explicitly track the melting interface. Each cell in the PCM domain has a value called the liquid fraction, which is the percentage of cell volume that is liquid. The enthalpy porosity approach is used by ANSYS Fluent to model the solidification and melting process [26]. Three procedures must be followed during the heating stage of the reflow process to perform the melting heat-transfer analysis for the PCM domain. These include melting heat-transfer analysis, pre-processing, and post-processing.

A. *Assumptions*

The following are the assumptions used in the numerical modeling:

1) Transient melting is thought to be a two-dimensional process.
2) In a liquid form, PCM moves incompressibly, non-Newtonian, and turbulently.
3) The PCM solder density, viscosity, and thermal conductivity all change piecewise linearly.
4) Volume expansion and viscous heating are neglected.
5) No heat is produced inside the PCM.

B. *Energy Equation*

The energy equations solved in ANSYS (Fluent) model are:

$$\frac{\partial(\rho H)}{\partial t} + \nabla . (\rho\vec{v}H) = \nabla . (k\nabla T) + S \qquad (1)$$

Where 'H' is the enthalpy, 'ρ' is the density, 'v' is the velocity of the fluid, and 'S' is the source term. The enthalpy 'H' is calculated as the sum of sensible and latent heat.

$$H = h + \nabla H \qquad (2)$$

Where 'h' is the sensible enthalpy at a point at a given instant of time; '∇H' is the latent heat.

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \qquad (3)$$

Where h_{ref} is the reference enthalpy, T_{ref} is the reference temperature, and Cp is the specific heat at a constant pressure of PCM.

$$\nabla H = \beta L \qquad (4)$$

Where β is the value of liquid fraction and L is the latent heat of PCM. The value of latent heat is zero when the material is solid (β=0) and L when the material is liquid (β=1).

$$\beta = 0 \quad if\ T < T_{Solidus} \qquad (5)$$

$$\beta = 1 \quad if\ T > T_{liquidus} \qquad (6)$$

$$\beta = \frac{T - T_{solidus}}{T_{Liquidus} - T_{Solidus}} \quad if\ T_{Solidus} < T < T_{Liquidus} \qquad (7)$$

Where $T_{liquidus}$ are the properties of the Solder used. [7], [23] [26].

C. *Phase Change Material (PCM) Melting Process*

1) *Pre-processing step*

a) Model Description

First, a computer-generated solid model of the solder junction must be created, complete with its dimensions and form. Figure 2 displays a geometric representation of the PCM domain utilized for simulation. A 2-D planer circle domain with a 4 mm diameter makes up the PCM domain. The following describes the PCM domain's border condition: The PCM domain's right-facing boundary side has complete insulation or q″=0 W/m2. The continuous heat flux boundary condition for the left-facing side of the PCM domain is q″=3000 W/m2.

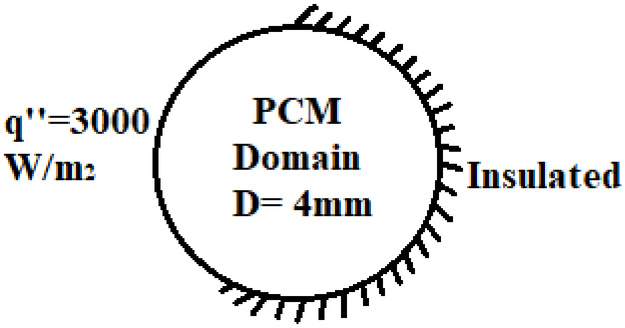


Fig. 2 Schematic diagram of the model

b) Mesh generation and simulation approach

To execute the numerical analysis, the solid must be dissected into a mesh system. The ANSYS (Fluent) 2020 R2 program is used to solve the issue using the finite volume approach. Pre-processing includes an important step called mesh size selection. The meshed model in Figure 3 has 2602 elements and 8003 nodes.

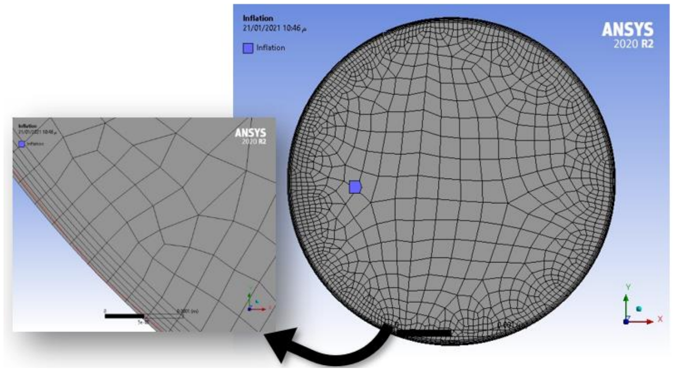


Fig. 3 Schematic diagram of the meshed PCM domain

The second-order upwind interpolation approach is used to discretize the convective components in momentum equations. First-order upwind interpolation is used to discretize the convective components in energy equations. The SIMPLE method is used to couple pressure and velocity, while PRESTO is used for pressure interpolation. In ANSYS (Fluent) 2020 R2, the computations are carried out by utilizing a standard commercial CFD package. When the residual of the energy, momentum, and continuity equations is smaller than 10-10, 10-8, and 10-5, respectively, convergence is attained (see Figure 4). The chosen time step is 0.1s. Ten iterations are allocated for each time step. The simulation was run on an Intel Core i7 CPU running at 2.4GHz with 12 GB of RAM.

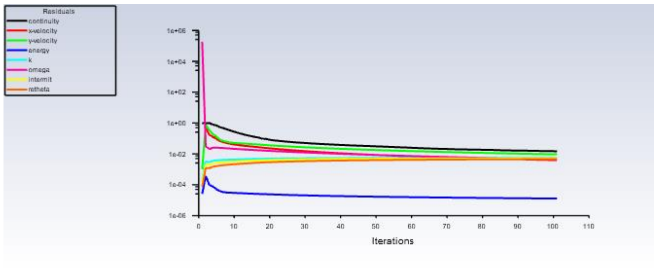


Fig. 4 shows the convergence of governing equations with iterations

III. RESULTS

A. Contours of Liquid Fraction

The numerical analysis of the melting of solder (95Pb-5Sn) in a 4 mm diameter circular domain with continuous heat flux heating from the domain's left side and complete insulation on the other side. For a full melting cycle of 1.5 minutes, the simulation's results were recorded at regular intervals of 15 seconds. The contours of liquid fraction, temperature, and velocity show the results.

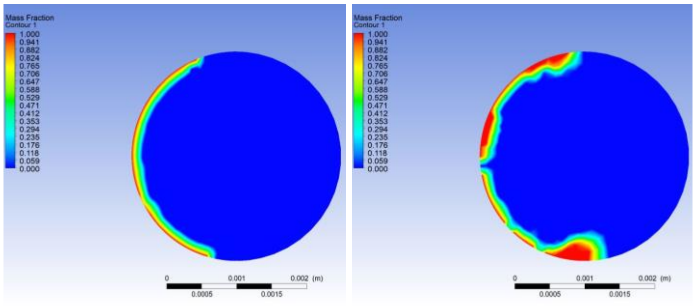
Figure 5 shows how the liquid fraction has changed over time. As time goes on, we can easily observe the form and motion of the melting interface. When a substance is liquid, it is represented by the color red (β=1), and when it is completely solid, it is represented by the color blue (β=0). The melting front is represented by the mushy zone, which divides the liquid and solid region. We can see that during the first 0–5 seconds of the melting process, the melting interface is roughly parallel to the left wall, indicating that conduction accounts for the majority of the early heat transfer. When 60 seconds have passed, the liquid PCM with the higher temperature rises goes downhill and repeats this cycle. The PCM chamber's PCM chamber melts 50% of the PCM in around 100 seconds. It has been observed that the melting rate is practically the same at the beginning, middle, and end of the melting process, and then rises. [25] also simulated the melting of PCM using ANSYS (Fluent), [3] reviewed the melting behavior of various configurations and. The results given by them also show similar melting behavior of PCM.

B. Contours of Temperature

The temperature contours and variation over time at regular intervals of 15 seconds are shown in Figure 6. The figure may be used to examine the melting process, showing that the greatest temperature reached during the beginning stage is 400^o C, the intermediate stage is 383^o C, and the final stage is 416^o C. Additionally, Figures 5 and 6 show that the PCM begins to melt at any point in the PCM domain when the temperature hits 312 degrees Celsius. The low-temperature zone is shown by the color blue. This zone's form is similar to the solid PCMs in the PCM domain, as seen in Figure 5. After 90 seconds, a red zone is beginning to form in the PCM domain closer to the left wall, and it is gradually getting bigger. This is due to the effects of the liquid PCM's turbulence. Constant temperature zones have been created because, at the end of the melting process, all of the PCM is in the liquid phase.

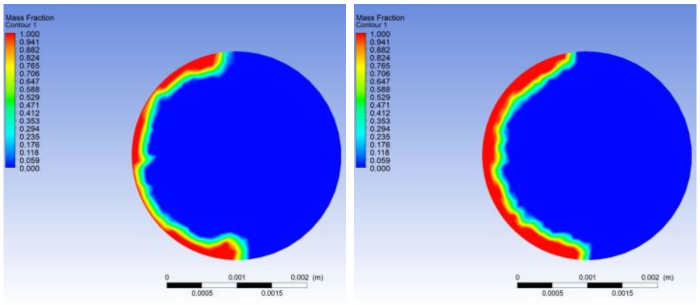
C. Contours of the Velocity vector

The contours of the velocity vector and the variation in velocity at regular intervals of 15 minutes each are shown in Figure 7. We can see that the area of the liquid PCM with the largest magnitude of velocity is close to the left (hot) wall and is colored red. All of the PCM is in a liquid condition at the end of the melting process, and its density remains stable. Thus, after full melting, the buoyancy effects are negligible. Therefore, at the end of the melting process, all the molecules become at rest.



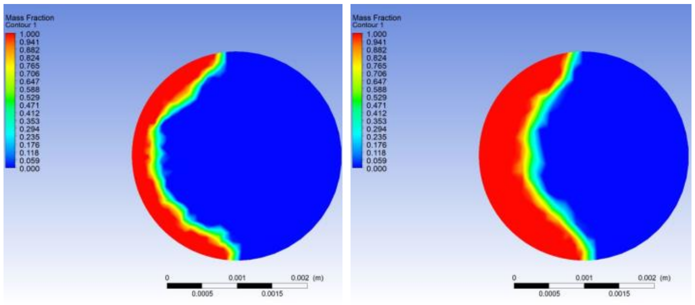
Time 5-Seconds

Time 15-Seconds



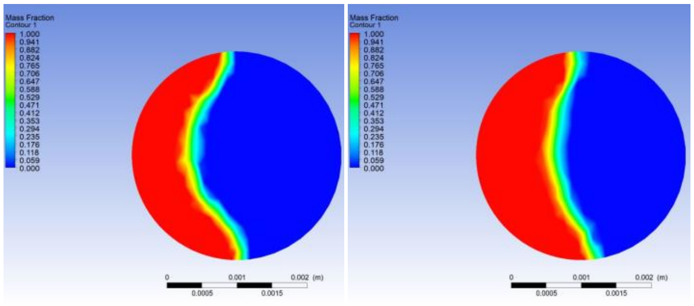
Time 20-Seconds

Time 30-Seconds



Time 45-Seconds

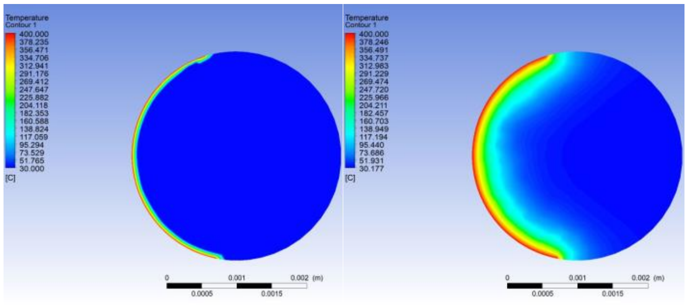
Time 60-Seconds



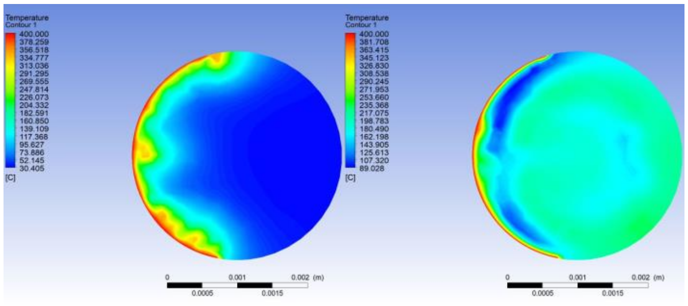
Time 75-Seconds

Time 100-Seconds

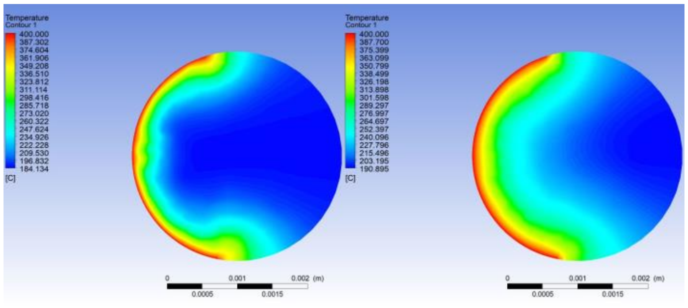
Fig. 5 Contours of the liquid fraction



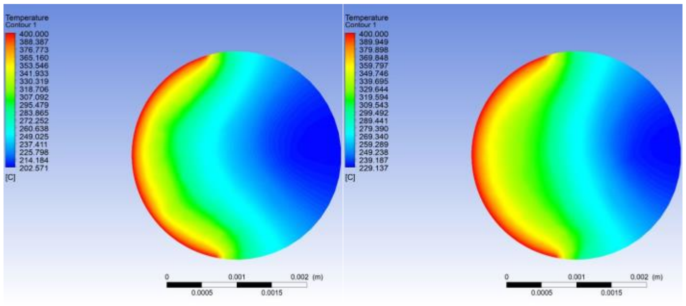
Time 5 Seconds Time 15 Seconds



Time 30 Seconds Time 45 Seconds

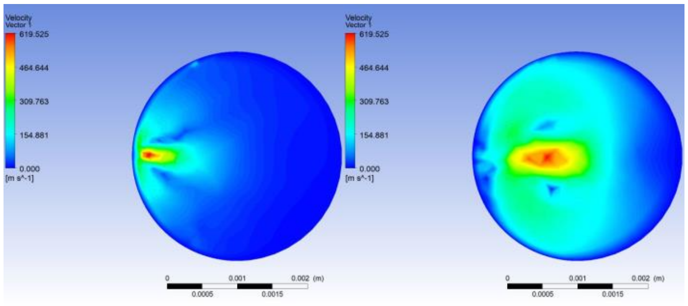


Time 60 Seconds Time 75 Seconds

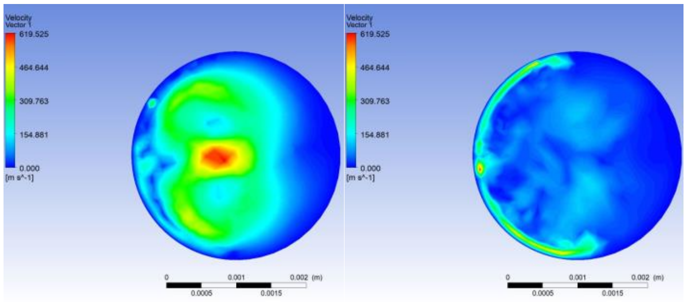


Time 90 Seconds Time 100 Seconds

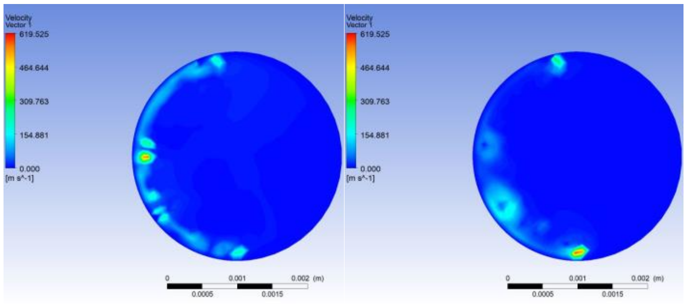
Fig. 6 Contours of Temperature



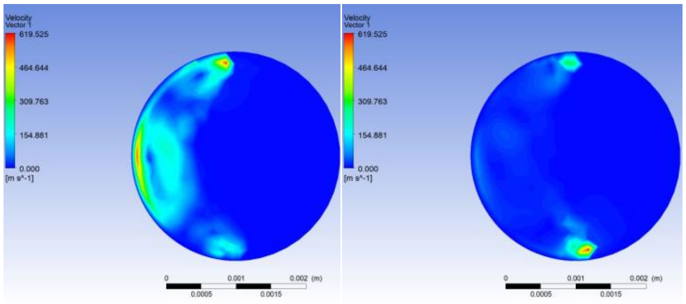
Time 5 seconds Time 15 seconds



Time 30 seconds Time 45 seconds



Time 60 seconds Time 75 seconds



Time 90 seconds Time 100 seconds

Fig. 7 Contours of Velocity

IV. CONCLUSIONS

The following conclusions may be taken from this numerical modeling and simulation of the PCM melting process under the condition of continuous heat flux:

1. In this case of side heating, wall melting begins on the right and moves leftward.
2. The melting rate increases as time proceeds. It is almost the same at the initial stages and increases in the middle and the end of the melting process.
3. Heat transfer happens mostly through conduction during the first 0–30 seconds of the melting process, changing to natural convection as the material continues to heat up.
4. Proper meshing and the selection of time steps should be done while simulating the melting problem on ANSYS (Fluent), otherwise there will be divergence error during the solution.

REFERENCES

[1] "A History of Welding". weldinghistory.org. Archived from the original on 25 April 2012. Retrieved 2 May 2018.

[2] Brady, George S., Henry H. Clauser, and John A. Vaccari. Materials handbook: an encyclopedia for managers, technical professionals, purchasing and production managers, technicians, and supervisors. McGraw-Hill Education, 2002, pp. 768–700.

[3] Dhaidan NS, Khodadadi JM. Melting and convection of phase change materials in different shape containers: A review. Renewable and Sustainable Energy Reviews. 2015 Mar 1; 43:449-77.

[4] Sarvar F, Conway PP. Effective modeling of the reflow soldering process: basis, construction, and operation of a process model. IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part C. 1998 Apr;21(2):126-33.

[5] G.K. Mui, X. Wu, K.X. Hu, C.P. Yeh, K. Wyatt, Solder Joint Formation Simulation and Finite Element Analysis, Electronic Components and Technology Conference, 1997, pp. 436–443.

[6] Yu H, Kivilathti J. CFD modelling of the flow field inside a reflow oven. Soldering & surface mount technology. 2002 Apr 1;14(1):38-44.

[7] Hassab MA, Sorour MM, Mansour MK, Zaytoun MM. Effect of volume expansion on the melting process's thermal behavior. Applied Thermal Engineering. 2017 Mar 25; 115:350-62.

[8] Lau JH. Thermal fatigue life prediction of flip chip solder joints by fracture mechanics method. Engineering Fracture Mechanics. 1993 Jul 1;45(5):643-54.

[9] Kapp Alloy & Wire, Inc. "Products". Kapp Alloy & Wire, Inc. Archived from the original on 16 July 2013. Retrieved 5 March 2013

[10] Fernandes, N. J., T. L. Bergman, and G. Y. Masada. "Thermal Effects During Infrared Solder Reflow—Part I: Heat Transfer Mechanisms." ,1992, 41-47.

[11] Kannapel MD, Przekwas AJ. CFD model of the reflow soldering process and equipment. Report of CFD Research Corporation, MR. 1997 Jan.

[12] Kim MR, Choi YK, Lee GB, Chung IY, Kim JD. Thermal investigation of an infrared reflow furnace with a convection fan. InInterSociety Conference on Thermal Phenomena in Electronic Systems, I-THERM V 1996 May 29 (pp. 211-216). IEEE.

[13] Pfeifer MJ. Solder bump size and shape modeling and experimental validation. IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part B. 1997 Nov;20(4):452-7.

[14] Lamberg P, Lehtiniemi R, Henell AM. Numerical and experimental investigation of melting and freezing processes in phase change material storage. International Journal of Thermal Sciences. 2004 Mar 1;43(3):277-87..

[15] Conway PP, Whalley DC, Wilkinson M, Williams DJ. Automated adaptive control of the reflow soldering of electronic assemblies. InTwenty First IEEE/CPMT International Electronics Manufacturing Technology Symposium Proceedings 1997 IEMT Symposium 1997 Oct 13 (pp. 229-236). IEEE..

[16] Bhatti, Pardeep K., Klaus Gschwend, Abel Y. Kwang, and Ahmer R. Syed. "Three-dimensional creep analysis of solder joints in surface mount devices." ,1995,: 20-25.

[17] Pielichowska K, Pielichowski K. Phase change materials for thermal energy storage. Progress in materials science. 2014 Aug 1; 65:67-123.

[18] Dudek R, Nylen M, Schubert A, Michel B, Reichl H. An efficient approach to predict solder fatigue life and its application to SM-and area array components. In1997 Proceedings 47th Electronic Components and Technology Conference 1997 May 18 (pp. 462-471). IEEE..

[19] Sarihan V. Energy based methodology for damage and life prediction of solder joints under thermal cycling. IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part B. 1994 Nov;17(4):626-31.

[20] Wahid MA, Hosseini SE, Hussen HM, Akeiber HJ, Saud SN, Mohammad AT. An overview of phase change materials for construction architecture thermal management in hot and dry climate region. Applied thermal engineering. 2017 Feb 5; 112:1240-59.

[21] White, Kent. "Brazing versus Soldering". TM Technologies, Tools & Methods for Better Metalworking. Archived from the original on 23 June 2017. Retrieved 2 May 2018.

[22] KIM WS, SONG HO. A study on the solidification heat transfer characteristics of heat storage system utilizing the PCM. Chemical Engineering Communications. 1988 Aug 1;70(1):157-70.

[23] Chiu YF, Tsai YL, Hwang WS. Mathematical modeling for the solidification heat-transfer phenomena during the reflow process of lead–tin alloy solder joint in electronics packaging. Applied Mathematical Modelling. 2003 Jul 1;27(7):565-79.

[24] Pao YH. Thermal fatigue fracture of 90Pb/10Sn solder joints. Advances in Electronic Packaging. 1992:291-300.

[25] Vikas AY, Soni SK. Simulation of melting process of a phase change material (PCM) using ANSYS (fluent). International Research Journal of Engineering and Technology (IRJET). 2017 Feb;4(5).

[26] Fluent AN. R2 User's Manual; ANSYS. Inc.: Canonsburg, PA, USA. 2020.

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Mustafa sabeeh carried out the simulation and the optimization.

Ammar Ghany was responsible for the Simulation and Statistics.