Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294
Volume 3, No 1, June 2024 [13-21]

Investigation of Inline Curing System Using Halogen Lamp on PET Substrate

Muhammad Najmi bin Zainal[1], Rd Khairilhijra Khirotdin[1*], Muhammad Ariff Fahmi Mohammad[1], Nurhafizzah Hassan[2]

[1]Additive Manufacturing Research Group, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.
[2]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.

Received 20 July 2023, Revised 25 September 2023, Accepted 30 September 2023

ABSTRACT

Halogen lamps have been seen producing faster high temperatures, which potentially reduces the curing time even further, but the current application was performed offline, thus causing the increase in manufacturing time and inaccuracy of the dimension of the ink track printed. Furthermore, the sample may also have been cured by surrounding temperature rather than the selected designated curing process. The inline curing process of conductive ink is required to prevent air cured and simultaneously reduce the manufacturing time. This study aims to evaluate the performance of the inline curing process through a halogen lamp on a PET substrate. The important curing parameters were determined, and the effect on manufacturing time, dispersion rate, and resistance were analyzed. The relationship between the significant parameters, including curing time and temperature, has also been established in which the resistance of the ink track is proportionated to the length of curing time and how high the temperature is applied. The conductive properties were increased when the temperature was elevated, reducing the curing time. However, increasing the time taken to cure the ink caused the substrate to wrap, deform a bit, and slightly damage the sample. It was also observed that the hardness and adhesion level became harder and stronger as the temperature increased. This concludes that the inline curing process using a halogen lamp is feasible on a PET substrate.

Keywords: Inline Curing, Halogen Lamp, Conductive Ink, PET Substrate.

1. INTRODUCTION

Printed electronics can be described as electrical devices created through various printing technologies that are administered to different types of substrates. The printing process of printed electronics significantly involves transferring metallic substances found in conductive ink onto a substrate. The conductive ink is crucial in this technology as the final material properties, along with its deterrence, are controlled by its chemistry. Besides that, the printed ink also relies on a drying mechanism, and this mechanism depends on several factors, including the printing process, type of printing ink (liquid, paste, organic solvent-based, etc.), speed of printing machines, substrates of printing material, types of printing product and characteristic of drying systems (hot air, infrared drying) [1]. Conductive inks are conductive materials used to create conductive patterns, which is the main part of electronic devices [2]. Graphite or any other conductive materials are mixed to create conductive inks. These conductive inks will need to be cured to achieve effective electrical conductivity [5]. The curing process facilitates the removal of unwanted solvents, thus leaving only metallic content behind. Conventional oven curing is

*Corresponding author: khairil@uthm.edu.my

commonly used to cure silver conductive ink [5, 7], but this technique also has a few limitations. Pre-heating for oven curing requires a longer duration to reach the designated high temperature, thus extending the time to cure the sample [1, 5, 7]. Furthermore, this technique uses a closed system and, if not properly controlled, will cause overheating. Overheating must be avoided as it will physically deform and damage the cheap and thin substrate, thus ruining any conducted experimentation. Laser, on the other hand, if used to cure the conductive ink, will yield a faster result [4] but is more expensive than other curing techniques. Another drawback of this method is that it requires advanced equipment and proper skills and knowledge to operate [8]. The curing time by localized laser curing process is determined by the total length and width of the ink track, so it can be summarized that a longer sample length will give a longer time to cure the ink [5]. Meanwhile, microwave heating is not suitable for heating metals because of the properties of metals reflecting microwaves and having few microns of penetration depth [6]. Precautionary measures also need to be taken when placing metal in a microwave to avoid the formation of electrical discharge that can harm the object. Hot presses using high internal stream pressures may damage the sample when not controlled properly [9], while hot air drying, despite producing high electrical conductivity, takes a longer time to cure ink tracks [10]. In a previous study, it was proven that halogen lamps can produce high temperatures at a faster rate [7]. Furthermore, the halogen lamp was chosen as a better replacement for curing silver conductive ink due to its lower cost and shorter pre-heating period compared to other curing methods.

However, halogen lamp curing is currently done offline, which may cause the ink track to be air-cured and consequently affect the accuracy of the dimension of the printed ink track due to the dispersion effect and lengthen the manufacturing time. The issue could be overcome by integrating the deposition process with the curing process in one continuous inline curing system. Integration, in general, is done by fusing two or more processes into one system that can do multiple tasks in a single operation [14]. The integration design can be created using problem-solving analysis such as brainstorming, morphological analysis, and weighted decision matrix. Integration provides numerous benefits, such as the integration of two-photon lithography (TPL) and holographic optical tweezers (HOT), which can aid in producing a sample in one process [15], thus reducing the manufacturing time to fabricate a sample. An integrated system can also help make complex interconnected structures that non-integrated processes cannot achieve. For example, inkjet printing with integrated electrostatic zipping actuators helps produce complex structures [16]. This means that integration is efficient in overcoming the limitation of a single non-integrated process. It can also be said that integrating two or more processes efficiently gives better results. Thus, the objective of this study is to evaluate the performance of the inline curing system via a halogen lamp on a PET substrate. The performance of the inline curing system was assessed by analyzing the resistance, hardness level and adhesion level of the cured ink track. Several relationships were established between variations of curing time and temperature to the resistance, hardness, and adhesion. The feasibility of the inline curing system on PET substrate was also determined accordingly.

2. MATERIAL AND METHOD

A silver-epoxy-based ink (Model AG806) was used in this study, as shown in Figure. 1 (a) due to silver conductive ink having high electrical and thermal conductivity properties and oxidative stable properties [3]. The suitable viscosity that allows a smooth deposition of ink was adjusted at 2.4 Pa.s and toluene was used to dilute the ink. A polymer sheet via a Polyethylene Terephthalate (PET) transparency sheet was chosen and used as a main substrate, as depicted in Figure 1 (b).

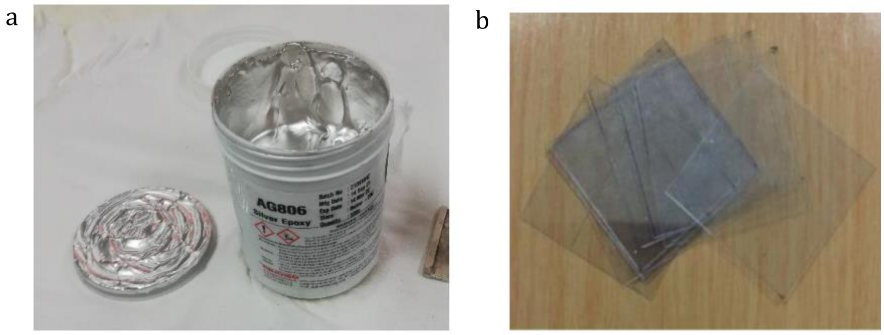

Figure 1: (a) Silver conductive ink (Model: AG806) (b) PET transparency sheet.

An inline curing system was developed by integrating the printing and curing process, whereby a halogen lamp was used as the heating mechanism for the curing process. An automated syringe-based deposition technique (Model: F4200N.1) shown in Figure 2 (a) was used to print the silver ink on a PET substrate. The technique is fast, precise, and capable of coping with different materials, such as conductive ink. A straight line shown in Figure 3 (a) and (b) with a length of 30 mm and width of 0.8 mm is designed and chosen because of its simplicity.

The ink track is required to be cured after printing to remove the unwanted solvents from the ink. This makes the metal content visible while promoting adhesion to the PET substrate. The printing and curing process is done using the integrated system shown in Figure 2 (b), in which the design selection is performed through a morphological chart illustrated in Table 1. The best suitable design was evaluated via a weighted decision matrix, and brainstorming was also used as a method of design selection whereby a design concept with the highest score was chosen for the integration.

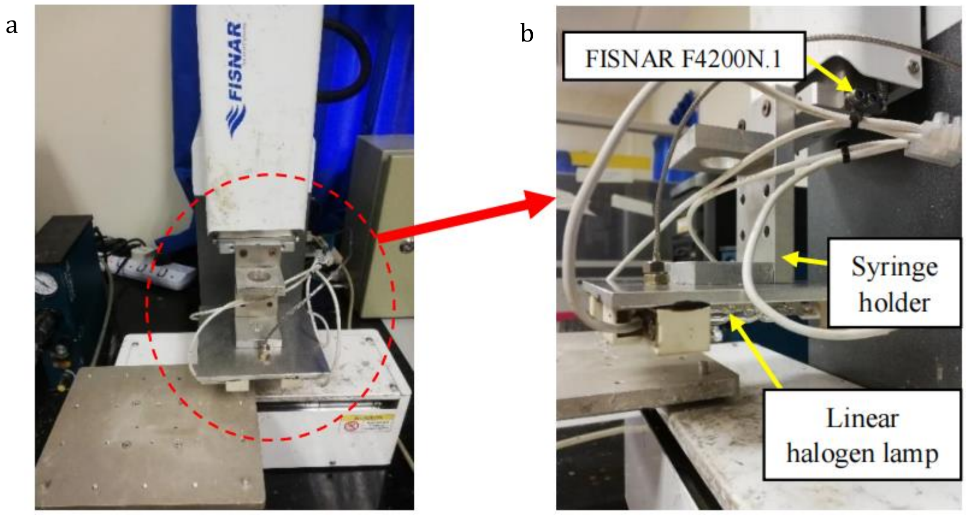

Figure 2: (a) Automated syringe deposition (Model: F4200N.1) (b) Installed inline curing system.

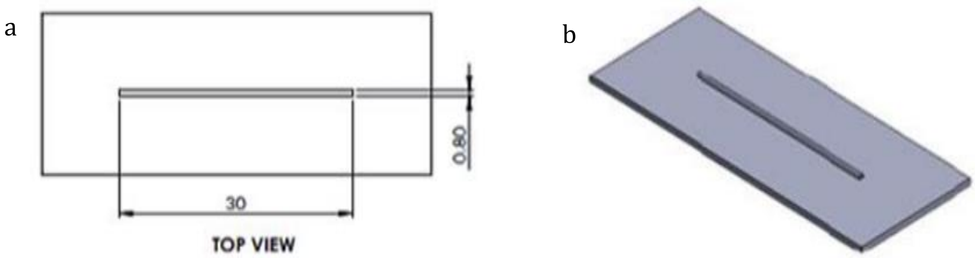

Figure 3: A straight-line ink track on a polymer substrate (a) top view (b) isometric view (unit in mm).

The optimum printing and curing parameters were selected based on the specifications tabulated in Table 2. The curing temperatures were set between 150°C and 190°C, and the curing times varied from 10 to 90 minutes. The process of curing using the inline curing system was started by adjusting the distance between the lamp and the work area to get an optimal space for an effective curing process. A sufficient length of 1 cm between the halogen lamp and the sample was maintained throughout the experiment. A total of 25 experimental runs were conducted in this study.

The analysis of the cured sample was measured using a digital multimeter to measure its electrical properties. The performance of the curing method is evaluated by analyzing the curing time and temperature applied to the conductive ink and the resultant electrical resistance of the printed ink track. A microhardness tester was used to assess the hardness level of the ink track by measuring the size of the impression left by the indenter. The adhesion test was conducted by cutting several small squares on the ink track, and tape was used to peel off the ink residues. The adhesion levels were then classified based on the 1B to 5B range, which determines the adhesion strength between the ink track and the substrate. The adhesion level is analyzed based on ASTM D3359.

Table 1: Morphological chart.

Required Function	Alternative Solution		
	Option 1	**Option 2**	**Option 3**
Type of halogen lamp	Linear halogen lamp	Circular halogen lamp	Bulb-type halogen lamp
Number of halogen lamp	1	2	3
Way of integration	Mount under the syringe deposition area	No mounting	Mount on the body of the syringe deposition machine
Halogen lamp voltage	200 Watt	2500 Watt	300 Watt
Distance between halogen and ink track	None	Near (1cm or less)	Far (>2cm)
Material used	Aluminum plate	Acrylic board	N/A
Type of joints	Non-permanent joint via screw	Permanent joint via rivet	N/A

Table 2: Printing and curing parameters.

Printing Parameter				
Pressure (kPa)	**Speed (mm/s)**	**Deposition Height (mm)**	**Nozzle Diameter (mm)**	**Viscosity (Pa.s)**
100.0	17.0	1.00	0.51	2.40
Curing Parameter				
Temperature (°C)		**Time (minute)**		
150-190		10-90		

3. RESULTS AND DISCUSSION

One of the successful printed samples after curing is shown in Figure 4 (a). Through observation, the printed ink track had a continuous and smooth straight line, as expected. Morphological analysis was conducted via an optical microscope to measure the physical characteristics of the silver conductive ink track. All samples displayed approximately 0.8 m of average width, as shown in Figure 4 (b), with an average percentage difference of 0.875%. A relationship was established whereby higher printing speed and constant printing pressure resulted in a thinner ink track. Most of the ink track was observed to have a constant thickness, which proved that a smooth printing process was successful. The viscosity of ink played an important role in delivering a smooth printing process. It was also discovered that the printing parameters used were suitable to produce the required physical characteristic of a silver conductive ink track.

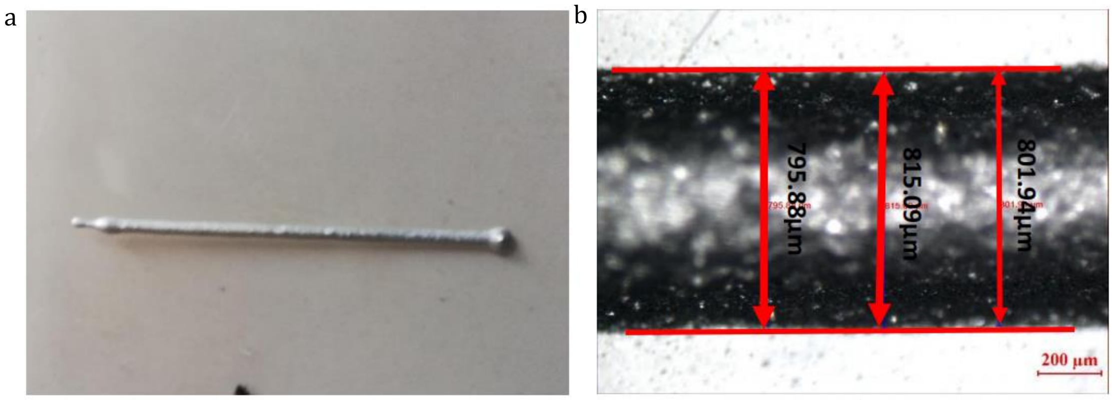

Figure 4: (a) One of the successful printed samples after curing (b) The width of the silver conductive ink track.

Table 3 shows the resistance results in which the highest resistance obtained was 9.2 Ω at 160°C with a curing period of 70 minutes, but at 90 minutes of curing time, the resistance slightly dropped to 8.3 Ω. The lowest resistance obtained was 0.9 Ω at 150°C with a curing time of 30 minutes.

Figure 5 shows the variation of resistance transition between inks cured with inline curing as a function of curing time and temperature. The resistance could not be determined at 150°C with a curing time of 10 minutes. This is because the ink was not fully cured while at 30 minutes, 50 minutes, 70 minutes, and 90 minutes showed the value of the resistance at 9 Ω, 2.0 Ω, 2.4 Ω, and 3.2 Ω, respectively. It was observed that the optimum curing time to fully cure the ink at 150°C was 30 minutes due to the resistance value being lower than 1 Ω; lower resistance allows more electricity to flow through, thus increasing the conductivity properties. Meanwhile, the resistance value increased as the curing time increased to 50 minutes, 70 minutes, and 90 minutes, respectively. Over-cured phenomenon caused the ink track to lose conductivity due to some of the silver metals being burnt out. The same phenomenon was observed transpired at 160℃, 170℃, 180℃ and 190℃ as the curing time increased. Based on the observation, the optimum curing time for each increment of temperature was 30 minutes (150℃ and 160℃) and 10 minutes (170℃ and 180℃) with resistance values of 0.9 Ω, 1.1 Ω, 1.8 Ω and 1.6 Ω were obtained respectively. This proves the resistance value decreases as a higher temperature is set with a shorter curing time. However, the resistance value at 10 minutes (190℃) resulted in a higher resistance value of 3.8 Ω while increasing the curing time slightly damaged the substrates. It can be concluded that the optimum curing time for 190℃ would be lower than 10 minutes.

The hardness test was conducted by utilizing the micro-hardness tester. A minimum and maximum load were identified first, and the minimum load of 980.7 mN (HV0.1) and 196.1 mN (HV2) were selected and applied. It was done to ensure the indenter presents a required diagonal shape mark on the surface of the ink track. It was found out that the suitable test load was 980.7 mN (HV0.1), as a diagonal shape was present on the ink track during testing, as shown in Figure 6 (a). Table 3 as well shows the overall result of the average hardness level, while Figure 7 shows the result of the hardness level.

Table 3: The results of resistance and manufacturing time of inline curing.

Run	Curing Parameter		Resistance (Ω)	Manufacturing time (minutes)	Hardness (HV)	Adhesion level (HB)
	Temperature (°C)	Time (minutes)				
1	150	10	N/A	19	N/A	1
2	150	30	0.9	38	32.46	2
3	150	50	2.0	60	34.68	3
4	150	70	2.4	80	36.98	3
5	150	90	3.2	100	38.10	3
6	160	10	6.6	21	33.34	2
7	160	30	1.1	40	36.28	3
8	160	50	1.4	61	37.60	3
9	160	70	9.2	83	49.50	3
10	160	90	8.3	104	51.55	3
11	170	10	1.8	23	24.96	3
12	170	30	1.0	44	33.50	3
13	170	50	2.8	64	39.94	4
14	170	70	2.1	84	69.59	4
15	170	90	2.3	105	70.49	4
16	180	10	1.6	29	35.46	4
17	180	30	4.1	48	36.46	4
18	180	50	3.6	69	37.51	4
19	180	70	3.7	89	40.37	4
20	180	90	4.5	110	41.14	4
21	190	10	3.8	34	34.46	4
22	190	30	N/A	N/A	N/A	N/A
23	190	50	N/A	N/A	N/A	N/A
24	190	70	N/A	N/A	N/A	N/A
25	190	90	N/A	N/A	N/A	N/A

It was observed that the hardness value was unavailable at 150°C (10 minutes) because the silver ink track was not fully cured, but at 30 minutes, 50 minutes, 70 minutes, and 90 minutes, the hardness level increased from 32.4598HV to 34.6803HV, 36.9791HV, and 38.09783HV respectively. It can be observed that the hardness value increased as the curing time increased. Based on Figure 6, similar patterns were observed at 160°C, 170°C and 180°C whereby the hardness value increased as the curing time increased, while at 190°C, hardness level can only be obtained at 10 minutes as further increasing the curing time damaged the substrates and ink. In addition, a previous study stated that the hardness level of the sample at 190°C is higher than 170°C, which means that increasing temperature increases the hardness level [11]. In summary, increasing the curing time as the temperature increased caused the silver ink track to harden as more solvents were removed, leaving only a strong bond of metallic particles.

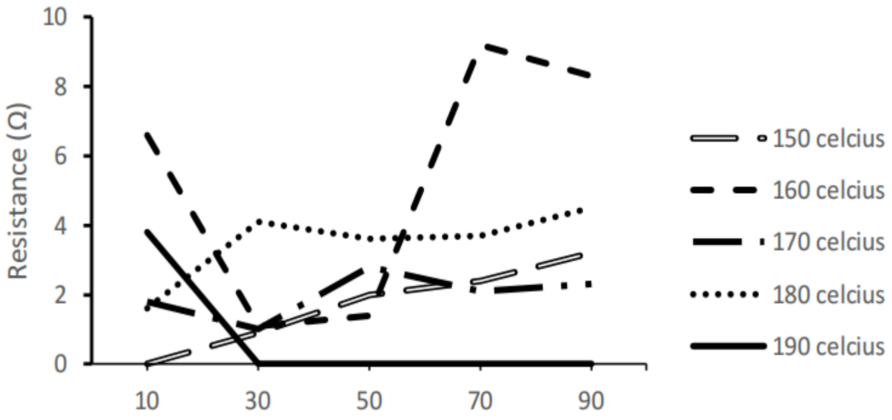

Figure 5: Variation of resistance transition against the curing time and temperature.

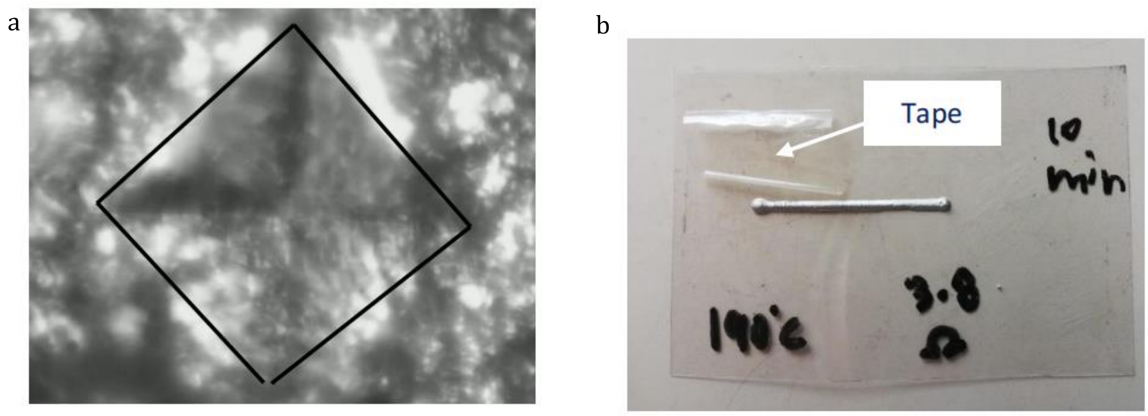

Figure 6: (a) Diagonal shape left by the indenter (b) Ink residues removed from a sample and stick on the tape during adhesion test.

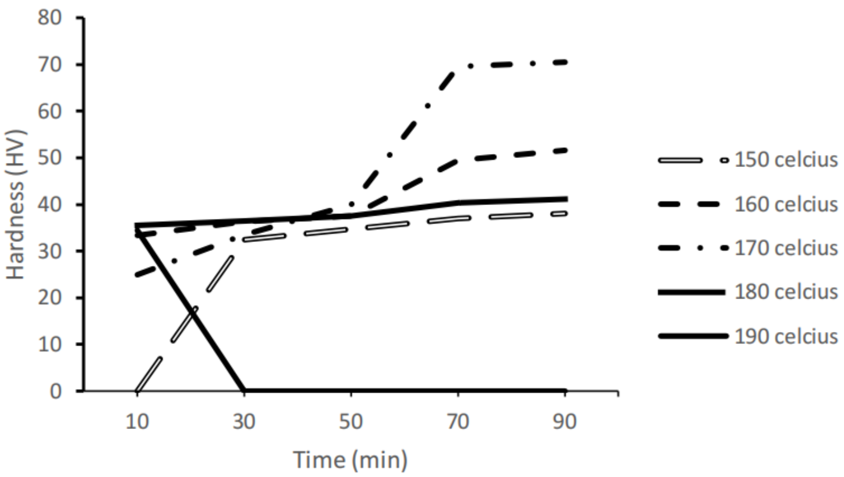

Figure 7: The hardness results against the curing time and temperature.

Furthermore, an adhesion test was also executed on samples to measure the adhesion level of the cured silver ink track. The adhesion level was analyzed based on the ASTM D3359. A crosshatch pattern was applied to the samples and then compared to its classification based on the percentage of removal of ink residues, as shown in Figure 6 (b). Table 3 shows the overall results of the adhesion test, while Figure 8 shows the result of the adhesion level. It was observed that at 180℃, the adhesion level remained constant at 4B at 10 minutes, 30 minutes, 50 minutes, 70 minutes, and 90 minutes curing time in which less than 5% of the ink residues were removed. This means the ink tracks were properly cured due to the metallic particle adhering more to the substrate's surface. A previous study has also stated that samples are completely cured when the adhesion area is less than 5% [12]. For curing temperature at 150℃, the adhesion level obtained was varied at 1B for a sample at 10 minutes curing times before increasing to 2B at 30 minutes and maintained onwards to 3B for samples of 50 minutes, 70 minutes, and 90 minutes, respectively. 5% to 15% of the silver ink particulates were removed for the adhesion level of 3B, while 15% to 35% and 35% to 65% of ink particles were removed for the adhesion level of 2B and 1B, respectively. This proved that increasing the curing time increases the adhesion level of the silver ink particulates. All the temperature variable shows a familiar pattern as 150℃ curing temperature. The curing parameter has also been observed to affect adhesion, as higher curing temperatures produce a better adhesion level [13]. In summary, the samples had a low adherence level at a shorter curing time but increased as the temperature increased with the curing time. Thus, it can be said that increasing the temperature and curing time increase the adherence intensity of the silver conductive ink track.

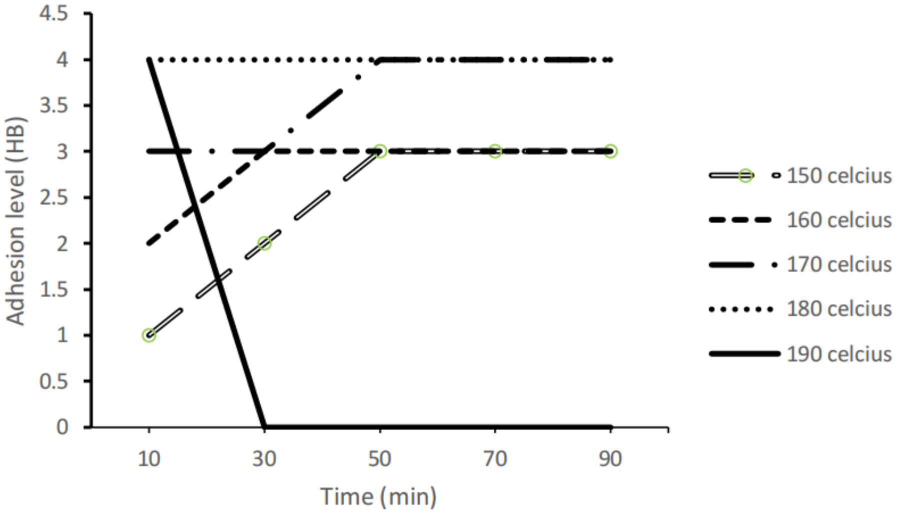

Figure 8: The adhesion results against the curing time and temperature.

4. CONCLUSION

In conclusion, it is possible to integrate the deposition and curing process into one system whereby the curing process by air could be avoided since the curing process starts immediately after the conductive ink is deposited onto the substrate. It can be concluded that increasing the curing temperature increases the ink's resistance. Higher temperatures also require shorter curing times to achieve lower resistivity. Moreover, hardness and adhesion results show that the silver ink hardened at higher temperatures is used in longer curing as more unwanted solvents evaporate, leaving a strong metallic bond and adding more force for metallic particles to adhere to the substrates. This proves the integrated system is feasible for curing the printed conductive silver ink.

ACKNOWLEDGEMENT

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through a TIER1 (vot Q357).

REFERENCES

[1] Saad, A.: Environmental pollution reduction by using VOC-free water-based gravure inks and drying them with a new drying system based on dielectric heating. Dr. Thesis (2007).

[2] Li, W., Sun, Q., Li, L., Jiu, J., Liu, X. Y., Kanehara, M., Minari, T., Suganuma, K. The rise of conductive copper inks: challenges and perspectives. Appl. Mater. Today, 18, (2020) p. 100451

[3] Titkov, A., Bukhanets, O., Gadirov, R., Yukhin, Y., Lyakhov, N. Conductive inks for inkjet printing based on composition of nanoparticles and organic silver salt. Inorg. Mater. Appl. Res., vol 6, issue 4 (2015) pp. 375–381.

[4] Sato, T., Fearon, E., Curran, C., Watkins, K., Dearden, G., Eckford, D. Laser-assisted Direct Write for aerospace applications. Proceeding of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol 224, issue 4 (2010) pp. 519-526.

[5] Roberson, D., Wicker, R., MacDonald, E. Ohmic curing of printed silver conductive traces. J. Electron. Mater., vol 41, issue 9 (2012) pp. 2553–2566.

[6] Eugene, W., Gupta, M. Characteristics of aluminum and magnesium-based nanocomposites processed using hybrid microwave sintering. Journal of Microwave Power and Electromagnetic Energy, vol 44, issue 1 (2010) pp. 14–27.

[7] Khirotdin, R., Ahmad, M., Nizam, M., Hassan, N. Investigation of Reducing Curing time of Silver Conductive ink using Halogen Lamp on Polymer Substrate. Proceeding of International Conference of Mechanical Engineering ICME21, (2021) pp. 5–9.

[8] Mustapha, S., Ye, L. Bonding piezoelectric wafers for application in structural health monitoring-adhesive selection. Research in Nondestructive Evaluation, vol 26, issue 1 (2015) pp. 23–42.

[9] Taghiyari, H., Rangavar, H. Effect of nano-silver on reduction of hot-pressing time and improvement in physical and mechanical properties of particleboard BioResources, vol 6, issue 4 (2007) pp. 4067-4075.

[10] Park, J., Rhee, S. A study of hybrid drying process to improve drying speed and electrical conductivity for roll-to-roll printing. Japanese Journal of Applied Physics, vol 49, issue 5 (PART 2) (2010) p. 05EC10.

[11] Kim, N. W.; Lee, D.-G.; Kim, K.-S.; Hur, S. Effects of Curing Temperature on Bending Durability of Inkjet-Printed Flexible Silver Electrode. Nanomaterials, vol 10, issue 12 (2020) p. 2463

[12] Wang, X. Q., Gan, W. P., Zhou, J., Xiang, F., Long, M., Peng, D. Effect of silver powders on a low curing temperature silver conductive adhesive. Journal of Materials Science: Materials in Electronics, vol 29, issue 21 (2018) pp. 18547–18552.

[13] Khinda, G., Kokash, M., Alhendi, M., Yadav, M., Lombardi, J., Weerawarne, D., Poliks, M., Borgesen, P., Stoffel, N. Effects of oven and laser sintering parameters on the electrical resistance of IJP nano-silver traces on mesoporous PET before and during fatigue cycling. Electronic Components and Technology Conference (2019) pp. 1946-1951.

[14] Gulledge, T. What is integration? Ind. Manag. Data Syst., vol 106, issue 1 (2006.) pp. 5–20.

[15] Chizari, S., Shaw, L. A., Hopkins, J. B. Simultaneous printing and deformation of microsystems: Via two-photon lithography and holographic optical tweezers. Mater. Horizons, vol 6, issue 2 (2019) pp. 350–355,.

[16] Schlatter, S., Grasso, G., Rosset, S., Shea, H. Inkjet Printing of Complex Soft Machines with Densely Integrated Electrostatic Actuators, Adv. Intell. Syst., (2020) pp. 1-14.