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INVESTIGATION OF THE EFFECT OF SPEED AND PRESSURE ON CONDUCTIVITY IN INKJET PRINTED ELECTRONIC DEVICES

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Abstract: *We can define printed electronics as the application of printing on a material by means of semiconductor, dielectric and electronic components. This process basically takes place by adding materials that will provide conductivity properties into the printing inks. In addition to printing with traditional printing systems, drop-on demand inkjet printing provides an important advantage in this field thanks to its non-contact and digital patterning capabilities. Therefore, the demand for inkjet printing printable inks based on high-performance electronics is also increasing to expand the scope of possible applications for printed electronics. In recent years, inkjet printing technology has become more and more popular due to its use in various applications such as photovoltaic cells, light-emitting diodes (LED), organic thin-thin transistors, displays, radio frequency identification devices (RFID), smart clothing and sensors. For these applications, the unique feature of inkjet printing technology is that it can print on a wide range of materials and is a digital, contactless and plateless system. We can count other advantages of this technology as low cost and savings from waste. These properties make the inkjet printing technique particularly suitable for printing conductive patterns on a variety of flexible substrates in the manufacture of electronic circuits or devices. The electrical conductivity on the printed material may vary depending on the substrate, printing speed and pressure. For this purpose, a specially prepared test scale with lines of different thicknesses was printed on the polyethylene film material with BENTSAI BT-HH6105B1 Portable Handheld Mobile inkjet printing machine. The effect of machine speed and pressure values on conductivity was observed in the prints made with silver-based conductive inks. As a result, it was concluded that the conductivity value increased as the printing pressure increased at constant speed, and on the other hand, the conductivity value increased as the printing speed decreased when the pressure was fixed.*

Keywords: conductivity, inkjet, printed electronics, printability, conductive ink

1. INTRODUCTION

The world is developing and changing according to our wants, needs, and everything change. Consequently, the need for advanced technological products is increasing. To respond to this increase, we must produce more and. Although the need for printed products, such as books and newspapers, has decreased, it can be said that there is an increase, not a decrease, when the printing industry are examined. The reason for this is packaging, labels, and high-technology printable products. In other words, the printing industry is not shrinking; on the contrary, it is growing daily and changing its shape. At this point, the use of printed electronics to produce new technologies has emerged as an option. This technology can be used in areas such as sensors, health products, displays, solar panels, wearable technologies, and VR games (Wang & Liu, 2016). When the products mentioned are examined and traditional production techniques are used, both time and conductive materials are lost. They are also difficult to manufacture. However, with printing systems, these products can be produced more easily and cheaper using less ink. Printed electronics are products that are easy to manufacture, inexpensive, shorter in time, and generally exhibit high performance. Owing to these advantages, it is used in many areas and there are new areas of use by day (Wu, 2017).
Printed electronics can be defined as the transfer of a conductive ink to the substrate of an electronic circuit element by means using a plate. This is similar to the traditional printing processes. According to the Organic Electronics Association, printed electronics are defined as “thin, light, flexible, and low-cost electronics” (Organic and Printed Electronics Association, 2022). As printed electronics evolve, this opens new doors to technology. These include smart packaging applications, smart transport systems, smart textiles, lighting and panel systems, and flexible displays. Depending on customer demand, it is used in many areas from the packaging industry to the automotive industry, from the pharmaceutical industry to the construction industry, and the health sector (Figure 1). In addition, wearable health products such as smaller scale games and augmented reality applications, smart roads and cars, and diabetes sensors can be produced with the help of printed electronics (Kantola et al., 2009). Many studies show that it will

enter our daily lives in many new areas such as invisibility, foldable and wearable screens, body integrated communication systems, and printed electronic products in the future.

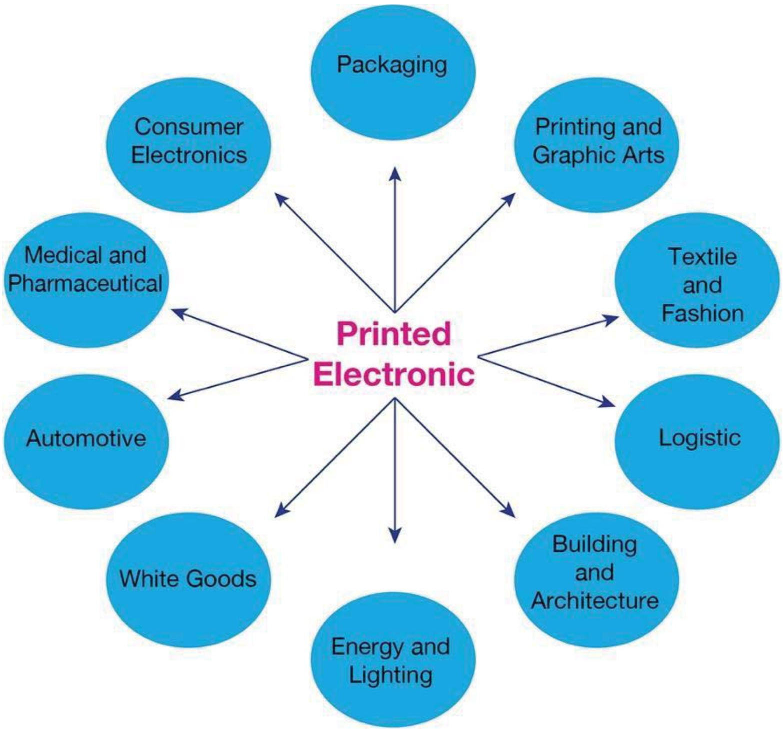

Figure 1: Printed electronics usage areas

The most important element of all electronic devices is the conductive structure of the metals that connect various components in the circuit. Conventional electronic systems are produced using photolithography, a complex and time-consuming multi-step process that requires expensive facilities and a variety of tools that generate large volumes of environmentally damaging hazardous waste. Vacuum deposition is also used in the manufacture of electronic devices. This process is not as costly as photolithography, but requires a large amount of energy to perform. In addition, the process is difficult to control over small areas, therefore, it is not suitable for high resolution patterns.

The global market demands high-quality and low-cost production methods for electronic devices that are both faster and cheaper than traditional production methods. There has been a worldwide effort to make these processes commercially available, and some have already been successfully commercialized. Printed electronics bring together two different fields; printing and electronics. Using traditional printing processes, inks based on metal nanoparticles (NPs) and metallo-organic complexes (MC) are used to produce building blocks of electronic products, such as transistors and diodes (Rao et al., 2022). The biggest advantage of printed electronics in the production of these components is the significant reduction in the cost of the electronic devices. Applications of printed electronics have previously been demonstrated in the manufacturing of batteries, LEDs, displays, speakers, sensors, and fully printed RFID tags. Flexible electronic devices are manufactured by placing single or multiple layers of functional materials, including paper, on polymer substrates.

The most important challenge in printed electronics is the formulation of functional inks. The formulation of functional inks is similar to that of printing inks; however, in order to be compatible with flexible surfaces, the printed pattern must provide good printability, good compatibility with the substrate, and low temperature processing (Patil, 2015), which is only possible with fluid or semi-fluid ink (Dang et al., 2014). Therefore, the dimensions of the metals used in this study should be reduced. However, in this manner, it is possible to produce ink from metals. Thus, these metals exhibit properties different from those of their normal sizes (Elzey & Grassian, 2010). To increase the effectiveness of the ink, the surface of the nanometal was modified with organic molecules. The metal obtained here can not only be called a pigment, but the product obtained is a functional ink (Schlisske et al., 2021).

Conductive inks consist of silver, copper or organic semiconductor materials. Many printing systems, such as inkjet, flexo, screen printing, and intaglio printing, are used in the production of printed electronics.

The ink rheology, viscosity, wettability, surface energy, and morphology of the substrate are effective for printing ink on the surface, as designed. These parameters play a significant role in the high resolution of printed electronics products. Therefore, these criteria should not be ignored when selecting the substrates. These substrates have also been used in the packaging industry. This allows for the production of low-priced, easily produced and easily accessible products. In addition, fibre materials such as polyesters are used in wearable devices (Cui, 2016).

Currently, the printed electronics market is dominated by nanosilver-based inks. Printed electronics is a highly material-oriented field. Inks must operate stably with the viscosity and surface tension values required for printing, and charge transfer via interconnected molecules or particles in the transferred ink film, which provide the necessary electronic functionality (Patil, 2015). The challenge in meeting these requirements is the correct formulation of conductive inks. In inks using metallic nanoparticles, the nanoparticles are closed with a protective shell (encapsulation) to obtain a stable distribution of particles (Choi, 2012). Graphene-based inks offer high conductivity, flexibility, high speed printing, and low temperature curing properties.

When the materials used for printed electronics are examined, one of the important parameters affecting the final product feature is the substrate material. The mechanical properties and different surface properties of the substrate affect the printability and print quality. Printed electronic applications on flexible surfaces determine the cost and production technique of the final product. Smooth, low porosity and high surface energy substrates are preferred for most printable electronics applications. When the printing materials used in printed electronics are examined, we can begin with low-priced and widely used paper. In addition to these advantages, this study is thermally stable. However, indentations and protrusions on paper surfaces create problems for printed electronics. For this reason, by applying surface smoothing processes such as sizing, coating or calendering on the surface of the paper, these indentations can be reduced, the surface can be modified, the porosity can be reduced and surface wetting can be achieved, thus higher resolution electronic applications can be made (Hoeng, Denneulin & Bras, 2016). Other materials used in printed electronics include polyimide films, and various plastic and steel films. For special applications, high purity film materials meet these requirements. Polyethylene terephthalate is the most commonly used substrate in the printed electronics industry (MacDonald, 2007). In addition, many polymeric film materials satisfy the requirements of printed electronics. However, surface modification and applications may be required to increase the interest in these film materials in functional inks (Cummins & Desimulliez, 2012). For example, polyethylene terephthalate films require thermal stabilization.

The ease of creating the desired pattern in the screen printing technique, which is the most widely used in the field of printing electronics, allows it to be used frequently in the field of electricity and electronics. The sieves can be either flat or rotary. In the screen printing process, conductive, dielectric, and highly functional materials other than carbon can be printed. Screen printing is a very suitable tool in terms of possibilities such as printing thickness and repetition required for textile antenna production.

Inkjet printing technology is very promising today, especially in the production of low-cost and disposable electronics for various applications such as displays and RFID tags. In recent years this technology has been adapted to a number of technology areas as a manufacturing tool such as displays, plastic electronics, tissue engineering and 3D printing. The major advantage of inkjet printing is its ability to produce consistent drop volumes in a desired location. Another of the greatest advantages of the inkjet printing system is that it enables us to print data that can be changed. Thus, it is possible to produce many different circuit elements in a short time.

In the study, the effect of speed and pressure change on the conductivity value in inkjet printing was determined by printing at different speeds and different pressures in a handheld printer inkjet printing machine with specially prepared conductive ink.

2. METHODS

Conductive ink for use in prints is prepared as follows, it will be mixed with 0.01 M $NaBH_4$ and 0.01 M polyvinyl pyrrolidone (PVP). Then, 0.1 M $AgNO_3$ was added dropwise to this mixture. The colourless mixture was stirred until it turned dark brown. This colour indicates the formation of silver nanoparticles. Then, glycerol was added to the mixture as a stabilizer, and the mixture was mixed for 15 min to obtain silver nanoparticles. Using the obtained silver nanoparticles, inkjet ink with the ratios in Table 1 was prepared. For this, first the resin was fluidized using a solvent, then solid silver nanoparticles were added and after its viscosity was adjusted with the remaining solvent, it was homogenized in an ultrasonicator and printed quickly.

Table 1: Conductive ink formulation

Contents	Ratio
Ag Nanoparticles	25
Vinyl Choloride/Vinyl Acetate Copolymer	15
Ethylene Glycohol	60
Total	100

In the study, prints were carried out at different speeds of 300, 500, 700, and 900 m/s and at different pressures of 90, 120, 150, and 180 bar on a handheld printer inkjet printing machine with specially prepared conductive ink. With these pressures, the effect of speed and pressure change on the conductivity value was determined. In addition, it has been observed whether there is a change in conductivity according to the change of line thickness by using lines of different thickness in the special scale created for the test print.
Bentsai bt-hh6105b2 thermal inkjet digital printer (Figure 2) was used as the printing machine in the study. Polyethylene film material was used as the substrate material. Polyurethane binder conductive ink containing silver nanoparticles was produced and used. The images of the printed conductive lines were taken with the Leica S8 APO microscope and it was examined whether the prints were carried out optimally or not. After printing, conductivity measurements were made with a multimeter.

Figure 2: Bentsai bt handheld thermal inkjet digital printing machine

3. RESULTS AND DISCUSSION

Silver nanoparticle and inkjet ink were prepared successfully. It was determined that the silver ink remained homogeneous for 4 hours and inkjet prints were carried out without any problems.
As a result of the printing, the conductivity measurement results obtained at a constant speed of 300 m/s (Figure 3), 500 m/s (Figure 4), 700 m/s (Figure 5) and 900 m/s (Figure 6) are given. In addition, conductivity measurement results obtained at constant pressure of 90 bar (Figure 7), 120 bar (Figure 8), 150 bar (Figure 9) and 180 bar (Figure 10) are given.
As seen in the figures, when the conductivity values of the prints made at constant speeds of 300, 500, 700 and 900 m/s at 90, 120, 150 and 180 bar pressures are examined, the conductivity value increases as the pressure increases at constant speed.

In addition, an increase in conductivity was observed in parallel with the increase in line thickness. Depending on the increased printing pressure, the amount of transmitted ink also increased and this caused an increase in conductivity.

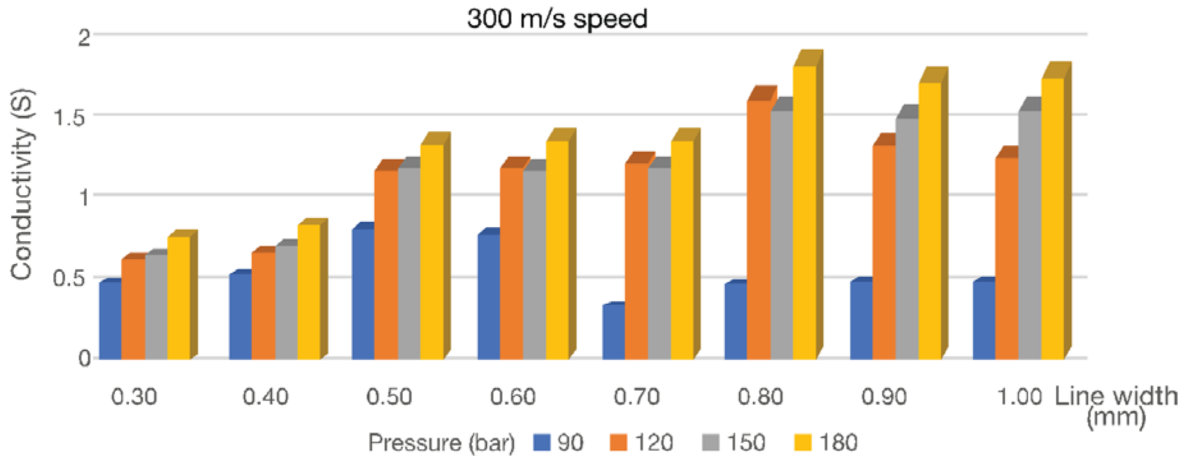

Figure 3: Conductivity values of lines printed under different pressure at a constant speed of 300 m/s

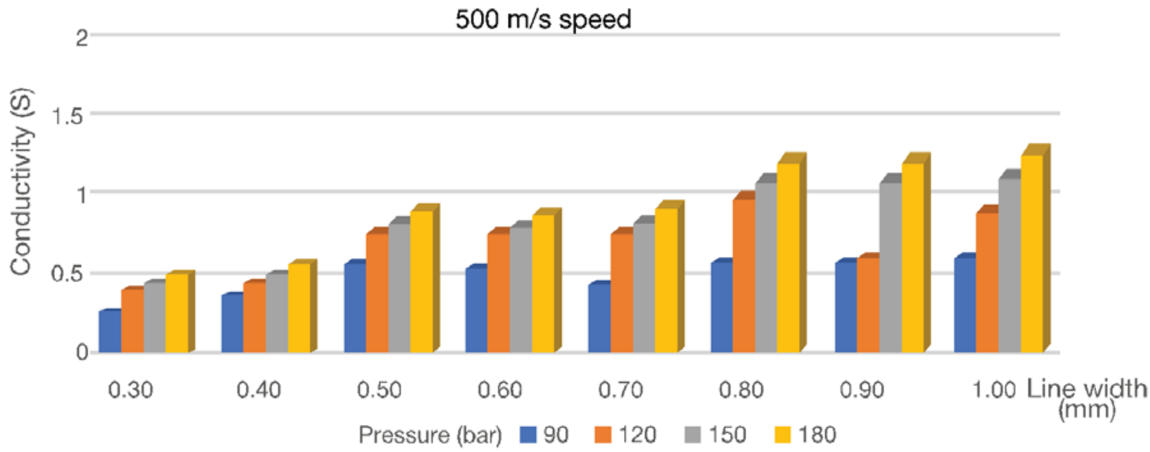

Figure 4: Conductivity values of lines printed under different pressure at a constant speed of 500 m/s

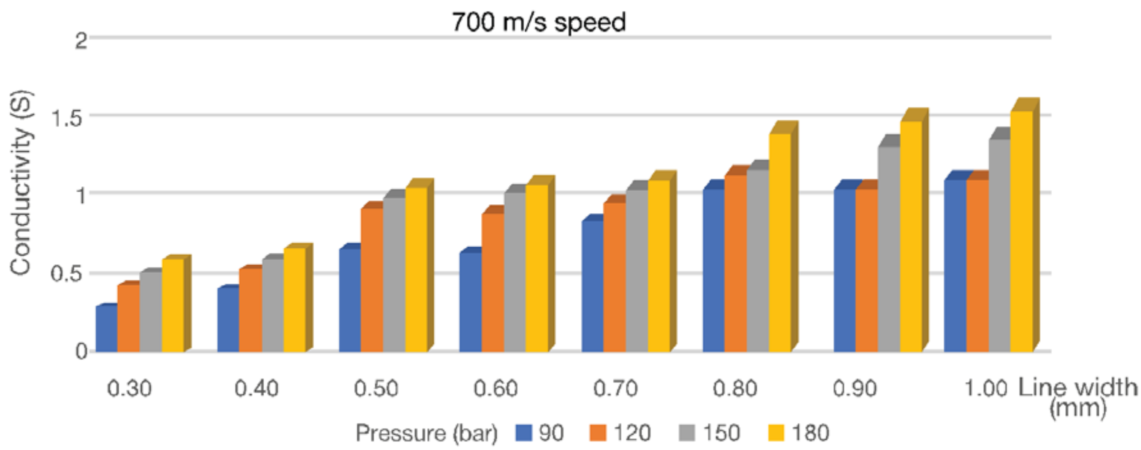

Figure 5: Conductivity values of lines printed under different pressure at a constant speed of 700 m/s

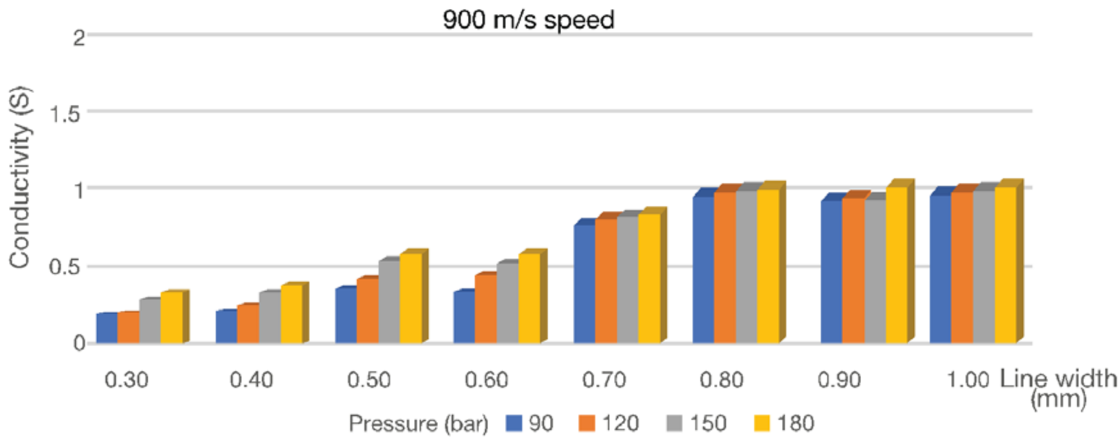

Figure 6: Conductivity values of lines printed under different pressure at a constant speed of 900 m/s

When the conductivity values obtained from the prints made at different speeds under constant pressure are examined (Figure 7, Figure 8, Figure 9, and Figure 10), it has been determined that the conductivity value decreases as the speed increases at constant pressure. In addition, the increase in line thickness also increased the conductivity value.

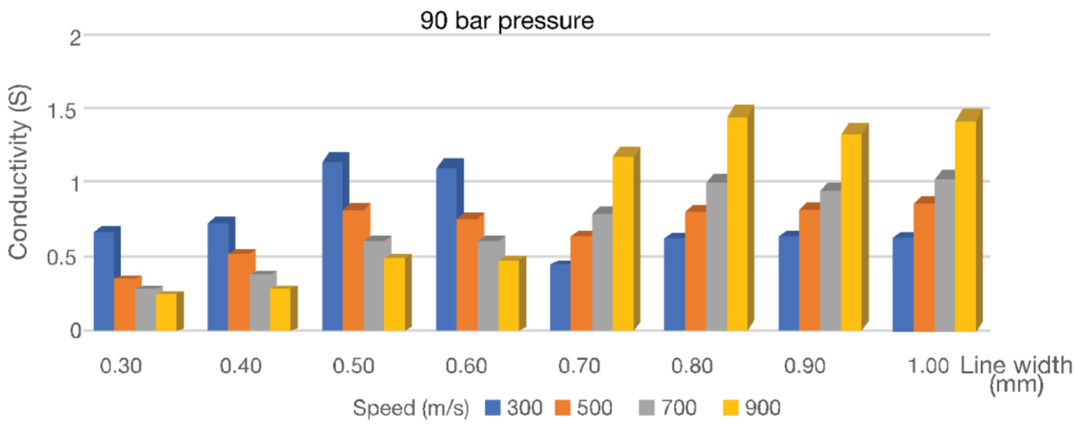

Figure 7: Conductivity values of lines printed at different speeds under 90 bar constant pressure

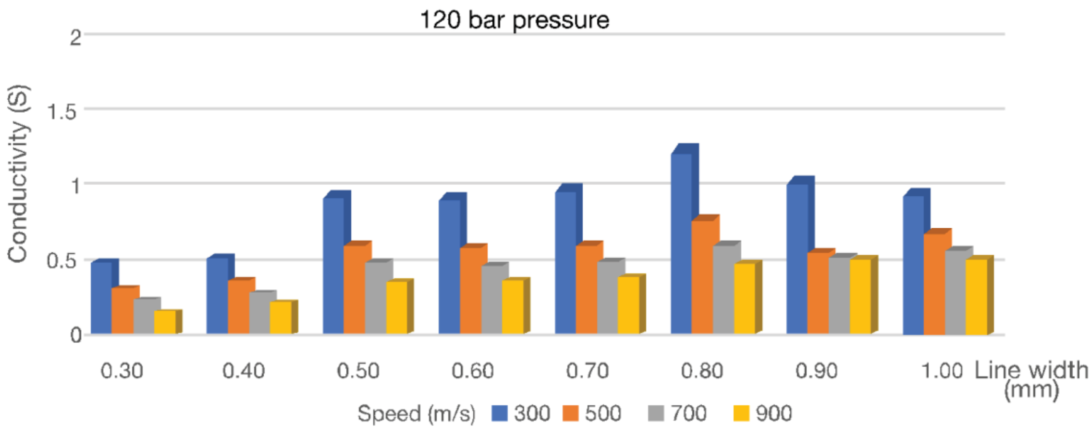

Figure 8: Conductivity values of lines printed at different speeds under 120 bar constant pressure

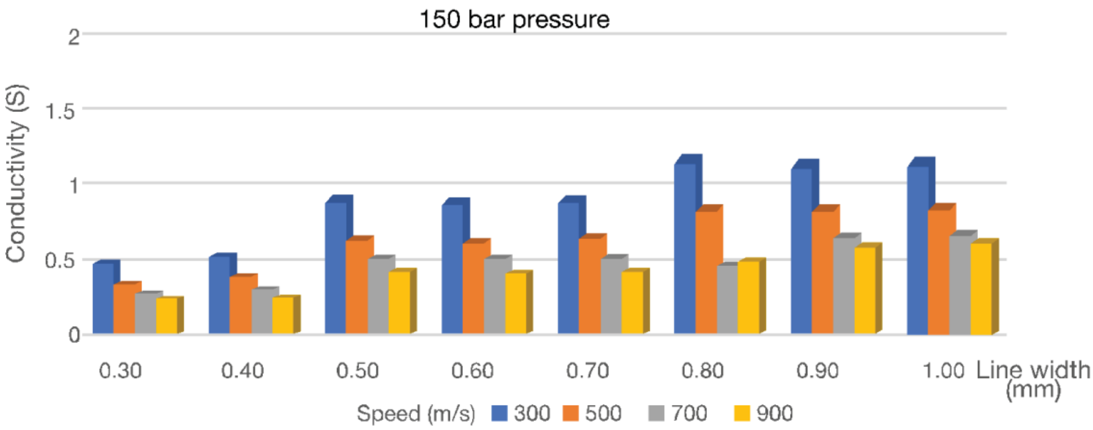

Figure 9: Conductivity values of lines printed at different speeds under 150 bar constant pressure

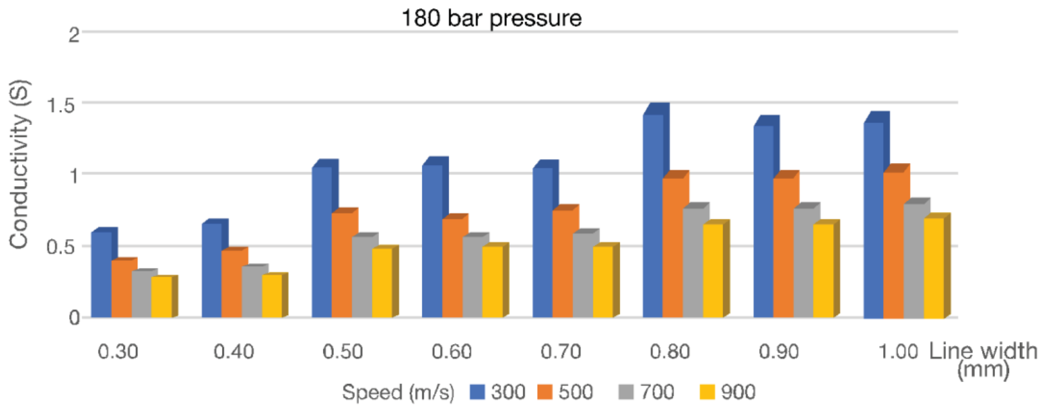

Figure 10: Conductivity values of lines printed at different speeds under 180 bar constant pressure

4. CONCLUSIONS

The increase in smart devices and their use in all areas of our lives, researches and studies on solar energy and other environmentally friendly energies increase the importance of printed electronics day by day. In addition to traditional printing methods, 3D printing systems are also preferred for printed electronics production. The printing system preference is mostly determined by the substrate material and the product to be produced, and the cost is also an important reason for preference. While the screen printing system is common in traditional printing systems, flexo or engraving methods are also used. In recent years, developments in digital printing systems, increasing diversity in printing materials, developments in ink and decreasing unit cost have made inkjet printing systems very popular. When we look at printed electronics in particular, the trend has evolved towards inkjet. Important R&D studies continue in inks, which is the most important issue for printed electronics.

In the light of the data obtained in the study, it has been determined that as the pressure increases and the line thickness increases, the conductivity value increases, while the conductivity decreases as the printing speed increases. The inkjet printing system will gain importance for the printed electronics whose market share is increasing by day. In addition, the development of organic inks instead of metal nanoparticle inks has made the subject even more important.

5. REFERENCES

Cui, Z. (2016) Printed electronics: materials, technologies and applications. John Wiley & Sons.

Cummins, G. & Desmulliez, M. P. (2012) Inkjet printing of conductive materials: a review. Circuit World. 38 (4), 193-213. Available from: doi: https://doi.org/10.1108/03056121211280413

Dang, M. C., Dang, T. M. D. & Fribourg-Blanc, E. (2014) Silver nanoparticles ink synthesis for conductive patterns fabrication using inkjet printing technology. Advances in Natural Sciences: Nanoscience and Nanotechnology. 6 (1), 015003. Available from: doi: https://doi.org/10.1088/2043-6262/6/1/015003

Elzey, S. & Grassian, V. H. (2010) Agglomeration, isolation and dissolution of commercially manufactured silver nanoparticles in aqueous environments. Journal of Nanoparticle Research, 12 (5), 1945-1958. Available from: doi: https://doi.org/10.1007/s11051-009-9783-y

Hoeng, F., Denneulin, A. & Bras, J. (2016) Use of nanocellulose in printed electronics: a review. Nanoscale, 8 (27), 13131-13154. Available from: doi: https://doi.org/10.1039/C6NR03054H

Kantola, V., Kulovesi, J., Lahti, L., Lin, R., Zavodchikova, M. & Coatanea, E. (2009) 1.3 Printed electronics, now and future. In: Y. Neuvo, & S. Ylönen (eds.). Bit bang rays to the future. Helsinki University Print, pp. 63-102

MacDonald, W. A. (2015) Latest advances in substrates for flexible electronics. In: Caironi, M. & Noh, Y. Y. (eds.) Large Area and Flexible Electronics. Wiley Online Library, pp. 291-314

Organic and Printed Electronics Association. (2022) Who is OE-A. Available from: https://oe-a.org/about-oe-a/who-is-oe-a [Accessed 5th March 2022]

Patil, B. H. (2015) Formulation and evaluation of soy polymer based, gravure printed resistive inks for applications in printed electronics. Master Theses, Western Michigan University, MI, USA

Rao, C. H., Avinash, K., Varaprasad, B. K. S. V. L. & Goel, S. (2022) A Review on Printed Electronics with Digital 3D Printing: Fabrication Techniques, Materials, Challenges and Future Opportunities. Journal of Electronic Materials, 1-19. Available from: doi: https://doi.org/10.1007/s11664-022-09579-7

Schlisske, S., Rosenauer, C., R√∂dlmeier, T., Giringer, K., Michels, J. J., Kremer, K., ... & Hernandez‚ÄêSosa, G. (2021) Ink formulation for printed organic electronics: investigating effects of aggregation on structure and rheology of functional inks based on conjugated polymers in mixed solvents. Advanced Materials Technologies. 6 (2), 2000335. Available from: doi: https://doi.org/10.1002/admt.202000335

Wang, X. & Liu, J. (2016) Recent advancements in liquid metal flexible printed electronics: Properties, technologies, and applications. Micromachines. 7 (12), 206. Available from: doi: https://doi.org/10.3390/mi7120206

Wu, W. (2017) Inorganic nanomaterials for printed electronics: a review. Nanoscale. 9 (22), 7342-7372. Available from: doi: https://doi.org/10.1039/C7NR01604B