INVESTIGATING THE TECHNOLOGICAL PROCESS OF ADHESION IN THE FABRICATION OF WEARABLE ANTENNAS

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Abstract: *The process of designing and creating antennas on textile materials (TM) (built into the clothing) is an extremely interesting and innovative process. In modern conditions, in most cases, the conductive elements of the wearable antennas are made of a special conductive fabric (CF), which is connected to the main TM of the sewing product. The textile materials from which the garments are made are used as substrates for the wearable antennas. The efficiency of the adhesion process between the textile substrate and the conductive fabric is one of the main factors on which the quality of wearable antennas depends. The present work aims to study and analyze the technological features of the adhesion process (between CF and the substrate) in the fabrication of wearable antennas. As a result of the conducted research, dependencies between technological factors of the adhesion process in the fabrication of wearable antennas have been established. The obtained results make it possible to choose effective operating modes according to the priorities of the real work environment.*

Keywords: *process of adhesion, conductive fabric, wearable antenna.*

1 INTRODUCTION

In recent years, textile materials (TM) have been increasingly widely used: non-standard and innovative application. They are used to create a number of sensor systems in the field of health care [1]. TMs are also used as a basis for embedding electronic elements for various purposes. Electronic textile design is also part of the education of high school students' [2]. The application of TM as substrates for wearable antennas [3-7] is also increasingly common.

The process of designing and creating antennas on TM (built into the clothing) is an extremely relevant, interesting and innovative process. However, a number of cause-effect relations in this area are not sufficiently clear. This requires a lot of research and analysis to refine them.

In modern conditions, in most cases, the conductive elements of the wearable antennas are made of a special conductive fabric (CF), which is connected to the main TM of the sewing product. The textile materials from which the garments are made are used as substrates for the wearable antennas.

The efficiency of the adhesion process between the textile substrate and the conductive fabric is one of the main factors on which the quality of wearable antennas depends. Some research has been conducted in this area. For example, [8] discuss some of the problem areas in relation to adhesion to textile fibres and fabrics. Satisfactory adhesion to fibres and fabrics may be obtained when the material is dry, but failure of the adhesive joints may occur during aftercare treatments, e.g. washing and dry cleaning treatments [8]. In [9] is considered the understanding of adhesion between a synthetic polymer and a second material. The second material may be inorganic, such as glass, or it may be another polymer but is assumed to be smooth [9]. In [10] different views concerning polymer-to-polymer adhesion were considered. In [11] the recent research efforts on polymer adhesion with a special focus on adhesion mechanisms are considered. In [12] an overview of adhesive bonding processes and products and their various applications in the textile industry is made. These studies [8-12] consider the general principles of adhesion between polymers. They do not specify the processes of adhesion between the conductive fabric and the textile substrate in the fabrication of wearable antennas. A number of studies have been conducted on the possibilities for the application of various TMs as substrates in the manufacture of wearable antennas [3-6]. Wearable antennas made out of conductive fabric on textile substrates were reported in the past [4]. However, the processes of adhesion between the conductive fabric and the main TM (the substrate) in the fabrication of wearable antennas (WA) have not been sufficiently studied.

The present work aims to study and analyze the technological features of the adhesion process (between CF and the substrate) in the fabrication of wearable antennas.

2 DISCUSSION AND ANALYSIS

To achieve the aim, it is necessary to study a number of important technological parameters of the adhesion process between CF and TM, from which the sewing product is made.

2.1 Conditions to execute the experiment

An innovative TM registered with a patent [13] for an invention was selected for the TM from which the sewing product is made. It is a double woven fabric (for winter sports, hunting and tourism) "Hunter'12", produced by "E. Miroglio SA" - Sliven, Bulgaria. Its characteristics are described in detail in [13]. Extensive studies of the dielectric constant of this TM were performed for one and two layers [3]. This motivated the choice of this TM for the current study. The dielectric constant of this TM with a polymeric binder (PB) for different number of layers was also studied [3]. However, the parameters of the adhesion process between this TM and the conductive fabric in the fabrication of wearable antennas have been not clarified. This is a prerequisite for planning research in the present work.

The research is carried out with conductive fabric PT230, manufactured by SHZHOU WANHE Electronic CO., LTD. It contains the following components: polyester (70±3%), copper (16±5%), and nickel (14±2%). Its characteristics are: mass per unit area 80±10 g/m^2; thickness 0.08±0.01 mm; width 1080±10 mm. The used polymeric binder (PB) is a double interlining mesh with paper. One of the main factors determining the mechanism of adhesion is the melting temperature of PB. The quality of adhesion also depends on a number of technological parameters. For example, at a higher temperature of the iron heating plate, PB melts faster. After conducting numerous preliminary studies, other cause-effect relations have been established. For example, if the hotplate temperature is too high, the PB melts very quickly. Then, even at low pressure, PB displays on the front side of the conductive fabric. This leads to an unacceptable deterioration in the quality of WA.

Determining the temperature with thermal paper is not precise enough, as the temperature values are read at a certain interval. For this reason, a modern method is used to measure the temperature to create feedback with the studied materials. The temperature is read with a special PERMESS device. The temperature sensors are thermocouples.

The temperature Tp [°C], recorded between the iron plate and the conductive fabric and the temperature Tpb [°C], recorded between PB and the main TM (the substrate) differ significantly. This requires planning experiments to refine the technological parameters of the adhesion process for the selected TM.

For this purpose, Experiment I is planned to establish the time to reach different temperatures Tpb. The experiment was performed with a TEFAL steam iron. The adhesion processes are carried out without steam.

Experiment I was conducted in four stages. The conditions for the implementation of the first stage are:

- PB is placed on CF (CF is cut with dimensions slightly larger than the dimensions of the designed antenna);
- the scheme of arrangement of PB on the conductive fabric is given in Figure 1, where: 1 - ironing board; 2 - CF; 3 - PB; 4 - the paper on which the PB is; 5 - the iron plate;
- the temperature of the iron plate - 120°C;
- the time for carrying out stage 1 of Experiment I was determined after conducting a number of preliminary experiments - 2 s.

In step 2 of Experiment I, the paper 4 of Figure 1 is removed.

In step 3 of Experiment I, the CF is cut to the exact size of the conductive elements of the projected antenna.

The conditions for carrying out stage 4 of Experiment I are:

- the temperature of the iron plate - 120°C;
- the scheme of arrangement of the thermocouples when reading the temperature is given in Figure 2., where: 1 - ironing board; 2 - CF; 3 - PB; 4 - TM, from which the article is made (the substrate for the wearable antenna); 5 - plate of the iron; 6 - position of the sensors (thermocouples) for temperature reading;
- three variants were investigated (in the fourth stage of Experiment I): variant 1 - the time for reaching Tpb to 90°C; option 2 - the time to reach Tpb to 100°C; option 3 - the time to reach Tpb to 110°C.

It is assumed that some well-known companies have studied the processes of adhesion in the fabrication of wearable antennas. However, their results are confidential or commercial. In light of the above, no information was found about the temperature which PB (Tpb, °C) must reach in order to achieve quality adhesion. However, it is important to define the adhesion quality criteria.

The process of making WA is extremely innovative. There are many unresolved issues related to its implementation.

For example, after numerous preliminary studies, it has been found that the adhesion strength immediately after removing the iron is very low. The product needs to be cooled.

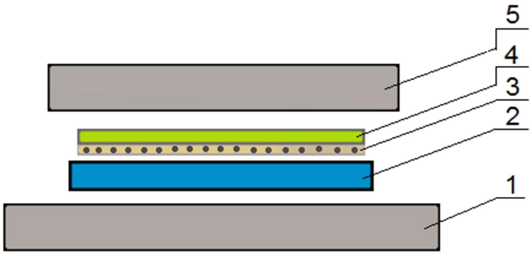

Figure 1 Arrangement of materials in step 1 of Experiment I

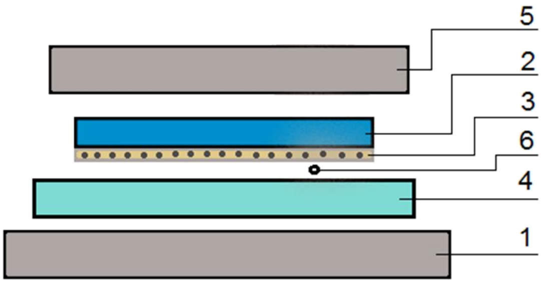

Figure 2 Arrangement of materials in step 4 of Experiment I

Then the adhesion strength is significantly higher.

It is logical that the quality of adhesion in the manufacture of WA also depends on washing and dry cleaning. This adhesion may depend on the exposure of the garment to direct sunlight, as well as on a number of other factors. In the present work, the resistance to adhesion after three washes was chosen as a quality criterion. The tests were performed after cooling the samples to ambient temperature. Washing was performed in a traditional program with an automatic washing machine at 30°C for 30 minutes. The choice of the washing temperature was made in accordance with the composition of the TM from which the product was made. It was found that in the samples made in variant 1, after the third wash, unravelling of the edges of the CF was observed. In some samples (for variant 1) separation of some ends of CF from the substrate was also observed. In the samples of variant 2 and variant 3, the ends of the CF were not unravelled and were not separated from the substrate. In variant 2 the energy and time consumption were lower. Therefore, as a criterion for qualitative adhesion, the following condition can be derived: Tpb=100°C.

During the preliminary experiments it was found that with increasing the pressure of the heating plate, the time to reach the required temperature of PB decreases. If the pressure is too high, it is possible for the PB to come out from the front of the CF. Therefore, more accurate consideration of the technological pressure factor is needed.

When working with the iron, the operator exerts a certain pressure. Considering this pressure is subjective. There is no possibility to measure and control this factor.

In the context of the above, Experiment II was planned, which was carried out on a fusing machine ATLAS-I. BALA-4-93 (stationary press type "drawer"). Thus, the pressure on the top plate becomes a controllable factor.

The conditions for conducting Experiment II are:

- the substrate, PB and CF are the same as in Experiment I;
- Experiment II is carried out in four stages;
- the technological parameters for carrying out stage 1, stage 2 and stage 3 of Experiment II are the same as in Experiment I;
- the technological parameters for the implementation of stage 4 of Experiment II are: a fusing machine ATLAS-I. BALA-4-93 (stationary press type "drawer"); pressure 44 N/cm^2; temperature of the press plate Tpp [°C] in three variants (variant 1 Tpp_1=120°C; variant 2 Tpp_2=130°C; variant 3 Tpp_3=140°C);
- stage 4 is finalized at T_{PB}=100°C.

2.2 Experimental results

The results obtained from the implementation of Experiment I and Experiment II are given in Tables 1 and 2. For both experiments, 3 repeated trials were made for each point in the experiment plan (m=3).

Table 1 Results from the conducted studies for duration of stage 4 of Experiment I

Study №, j	**Time t [s]**		
Variant №, i	t_1	t_2	t_3
V_1 Tpb=90°C	7.4	8.1	6.8
V_2 Tpb=100°C	12.6	13.1	11.9
V_3 Tpb=110°C	17.2	16.8	18.5

Table 2 Results from the conducted studies for duration of stage 4 of Experiment II

Study №, j	**Time t [s]**		
Variant №, i,	t_1	t_2	t_3
V_1 Tpp=120°C	8.9	10.1	9.1
V_2 Tpp=130°C	7.6	7.2	7.1
V_3 Tpp=140°C	6.2	6.4	5.3

2.3 *Discussion of experimental results*

It is necessary to check the reproducibility of the process, which is reduced [14, 15] to a check for consistency of dispersion (by Cochran's C test):

$$G_C = \frac{S_{i\max}^2}{\sum_{i=1}^{B} S_i^2}; \quad (1)$$

$$G_T \begin{Bmatrix} f_1 = m-1 \\ f_2 = B \\ r = 0{,}05 \end{Bmatrix} \quad (2)$$

where *m* is the number of repeated trials for each variant, *B* - number of variant, f_1 and f_2 - degrees of freedom, *r* - significance level.

The results for the calculated and tabulated value of the Cochran's C test for Experiment I are:

$$G_{C,I} = 0{,}5001; \quad G_{T,I} = 0{,}8709 \quad (3)$$

Therefore, intra-group variance does not differ statistically and the study process for Experiment I is reproducible.

The results for the calculated and tabulated value of the Cochran's C test for Experiment II are:

$$G_{C,II} = 0{,}5005; \quad G_{T,II} = 0{,}8709 \quad (4)$$

Therefore, intra-group variance does not differ statistically and the study process for Experiment II is reproducible.

As a result of the conducted experiments, the relationship between the temperature which PB reaches and the time required for this was established (under the same other conditions of the experiment - Table 1).

The data in Table 2 show that as the temperature of the press plate increases, the adhesion time decreases.

For each of the investigated variants of Experiment II, the adhesion between the substrate and CF was very good. No defects were observed on the samples. Each of the studied samples can be considered as high quality. Therefore, the required amount of time and energy can be used as a criterion for efficiency. The results in Table 2 show that minimum time is required for variant 3 in step 4 of Experiment II. The difference in time required for variant 1 and variant 2 is small (3-4 s). The difference in energy required for variant 1 and variant 3 is relatively larger. On the other hand, raising the temperature of the press plate to 140°C will also lead to a significant increase in the temperature of the working environment. For these reasons, it is proposed to use variant 1 of Experiment II in the present work.

In general, the results obtained make it possible to select the adhesion conditions (upon receipt of WA) according to the specific performance requirements.

3 CONCLUSION

The present work investigates the conditions for the implementation of the adhesion process between CF and the substrate in the fabrication of WA. Innovative textile materials and modern methods and devices for temperature measurement are used.

A criterion for finalizing the adhesion process is proposed. A technological variant for performing the adhesion with a fusing machine is proposed. Thus, the pressure becomes a controllable factor.

Specific values of the time for the implementation of the adhesion process under different technological operating conditions have been established. The reproducibility of the conducted studies has been proven.

Dependencies between technological factors of the adhesion process in the fabrication of WA have also been established.

The obtained results make it possible to choose effective operating modes according to the priorities of the real work environment.

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