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Study of Adhesion of Physical Vapor Deposition Coatings on Functional Textile with Laser Post-processing

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Abstract. **Functional textile are one of the most critical fields in the textile industry and textile materials science. In recent years, advanced technologies in textile processing have become relevant in order to improve its usability. In the production of various types of functional textile, one of the methods is the modification of textile surfaces. To improve the properties of the textile surface, magnetron vacuum sputtering and laser post-processing technologies can be used, which in general gives the material new or improved properties and functionalities. In this study, mixed fiber fabrics containing polyester, protal and cotton fibers are used to determine how laser post-treatment of the metalized fabrics impact the adhesive properties between fabric and deposited metal. The following materials were used for magnetron vacuum sputtering for functional textile coatings: Cu, Al, Ti, Ag. Individually or by combining these metals, it is possible to assign the textile such properties as: electromagnetic, UV and IR radiation shielding; antistatic, antibacterial, hydrophilic and hydrophobic properties, as well as increasing wear resistance. In this study a 100 W continuous wave CO_2 laser with a wavelength of 10.6 µm is used for post-treatment of magnetron vacuum sputtered modified textile surfaces. The study's conclusions point towards a tailored approach in determining linear energy densities that bolster adhesion for each metal-textile combination, which is essential for the development of durable and functional advanced textile. The patterns noted in the adhesion strengths, influenced by different energy densities and metal types, highlight the intricate relationship between the thermal impact of laser treatment and the inherent characteristics of the metals deposited. Some metals demonstrated improved adhesion at lower energy densities. However, a general trend emerged showing a reduction in the strength of adhesion as the energy density increased, especially when surpassing certain energy levels.**

Keywords: functional textile, laser post-processing technologies, magnetron vacuum sputtering, peel-off tape adhesion test.

I. Introduction

Functional textiles are one of the most important fields in textile industry and textile materials science. They include breathable, heat and cold-resistant materials, ultra-strong fabrics (e.g. as reinforcement for composites), new flame retardant fabrics (e.g. intumescent materials), optimization of textile fabrics for acoustic properties, etc. Functional textiles became more and more important materials for various applications and interest in them grew year by year [1].The purpose and perception of textile materials are changing, from simple protection to clothing with new functionalities and added value [2].

“Functional clothing” can be defined as “a general term that includes all types of clothing or sets of clothing that are specifically designed to provide the user with predetermined performance or functionality in addition to normal functions” [3]. This type of garment can be made using a high-performance fiber, a new finish, or a significant modification of a traditional material. Clothing must perform some specific functions, which

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may be protecting a person from a hazardous work environment [4].

Magnetron sputtering technology is a promising method for the surface modification of textiles. The use of magnetron sputtering technology can impart textiles anti-static, antibacterial, anti-ultraviolet, electromagnetic shielding, electrical conductivity and other single or composite properties [5]. The magnetron sputtering method has the advantages of controllable film thickness, high purity, high speed and low temperature, favorable adhesion, easy operation, and environmental friendliness, etc. [6,7].

Lasers are utilized for processing various materials, including textiles [8,9,10]. Utilizing lasers for heat treatment in experiments with metal-coated textiles is critically important due to lasers' unique ability to deliver precise, controllable, and localized heat [11]. This precision is crucial for ensuring consistent quality and integrity of the coatings without damaging the underlying textile substrate. Lasers enable fine-tuning of heat application, allowing researchers to systematically study the effects of various treatment parameters on material properties [12]. This level of control is unmatched by traditional heat treatment methods and is essential for developing advanced materials with specific characteristics.

The aim of this study is to examine the effects of CO_2 laser post-processing on the adhesion properties of physical vapor deposition (PVD) coatings on functional textiles. Tasks:

1. Investigate the adhesion strength of metals (Cu, Al, Ti, Ag) when coated on textile fabrics using magnetron sputtering and subsequently heat treated with a CO_2 laser.
2. Analyze the impact of varying laser linear energy densities on the adhesion properties of the metalized textiles.
3. Conduct comparative analyses using peel-off tape adhesion tests to quantify the adhesive strength and evaluate the effectiveness of laser post-processing in enhancing the functional properties of the textiles.

I. Materials and Methods

A. Fabrics

Mixed-fiber fabrics, composed of polyester and cotton fibers, are chosen for this study because they combine the durability of synthetic materials with the comfort of natural fibers. Polyester provides resistance to wear and lower water absorption, while cotton offers high breathability and comfort. By combining these two fibers, a material suitable for various usage needs is obtained, for example, can be used for work clothes and casual uniforms. The most important blend in the industry which is still in use, as the optimum performance fabric from KLOPMAN International, blend of 65% polyester / 35% cotton [13,14]. For comparison, a third fabric sample is used which has a different fiber composition and fire-retardant properties. The third fabric sample contains Protex Q fiber which is "the only modacrylic which has been specifically designed for PPE use and is Oeko-tex Class 1 compliant and REACH ready" [15]. In the research, samples of two different types of fabric weave (twill and derived canvas weave (rip stop)) with slightly different surface densities of 220 g/m² ±5% and 250 g/m² ±5% were selected. Characteristics of fabrics can be observed in Table 1.

Table 1 Characteristics of selected fabrics

Fabrics	A	B	C
Fiber composition	65% Polyester, 35% Cotton	65% Polyester, 35% Cotton	55% Protal, 44% Cotton, Antistatic 1%
Weave	Twill 2x1 Z	Rip stop	Twill 2x1 Z
Weight g/m²±5%	220	250	250
Finish	Crease Resist		

B. Sputtering process

The magnetron sputtering is carried out by SIDRABE Magnetron Sputtering System: Vacuum Deposition System for R&D purpose SAF M. The machine is equipped with 2 magnetrons for simultaneous coating of 2 metals (1 magnetron is used for a given process) and a rotating base for uniform coating of the material to be coated over the entire sample area shown in Fig.1.

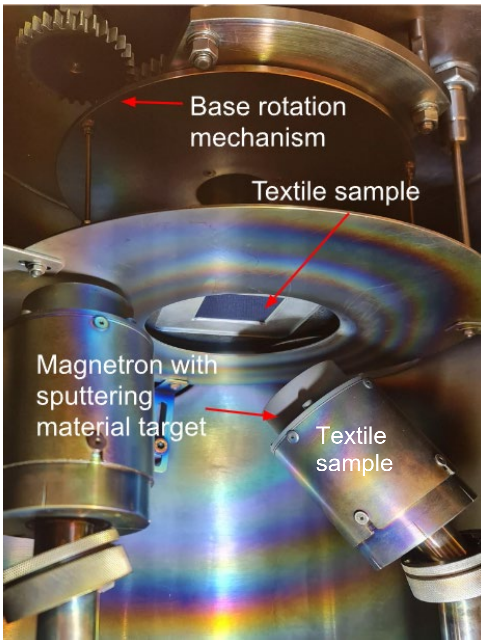

Fig. 1. Magnetron sputtering machine set-up.

Textile samples with a sputtered area of 48mm x 48mm for each material have been prepared for laser processing.

C. Magnetron sputtering

The target materials for sputtering were selected such metals as copper (Cu), titanium (Ti), silver (Ag), aluminum (Al), because of findings of other authors which such metal sputtering can give the base material: hydrophobicity, EMF shielding, IR shielding etc. [16,17,18,19]. The sputtering parameters used can be observed in Table 2.

TABLE 2 MAGNETRON PARAMETERS USED IN THE SPUTTERING PROCESS

Material (CAS Number of the elements)	**Al** (7429-90-5)	**Ag** (7440-22-4)	**Cu** (7440-50-8)	**Ti** (7440-32-6)
Deposition time, s	120	150	150	270
Pulse duration, µs	1,2	1,5	2	1,5
Pulse frequency, kHz	320	250	20	250
Power (used as setpoint), W	300	250	250	250
Coating Thickness, µm	50	60	80	85

Sputtered metal properties such as heat capacity, melting temperatures and heat conductivity could be observed in Table 3.

TABLE 3 DEPOSITED METAL MATERIAL PHYSICAL PROPERTIES

Material	**Al**	**Ag**	**Cu**	**Ti**
Heat conductivity, W/m*K	247	430	398	17
Melting temperature, °C	660	962	1084	1668
Heat capacity, J/g ° C	0.90	0.237	0.385	0.523

From available resources the reflectance coefficients of a choosed sputtered metals for a CO_2 laser wavelength are 0.91 for Ti [20] while Al, Ag and Cu have reflective coefficients of approximately 0.97 [21].

D. *Laser system*

In the process of heat treatment of a metal-coated fabric, authors utilized a carbon dioxide (CO_2) gas laser. Specifically, a Suntop ST-CC9060 continuous wave CO_2 laser system, which operates at a wavelength of 10.6 micrometers which corresponds to an infrared spectrum and can reach a maximum average power of 100 W. This laser system, equipped with 2 axis CNC-controlled beam steering, was employed to scan the textile samples. Principal scheme of an experimental set up of laser processing could be observed in Fig. 2.

Laser scanning path was controlled via computer with a principal scheme demonstrated in Fig.3. Should be noted that the laser treatment corresponds to the "Laser on" area.

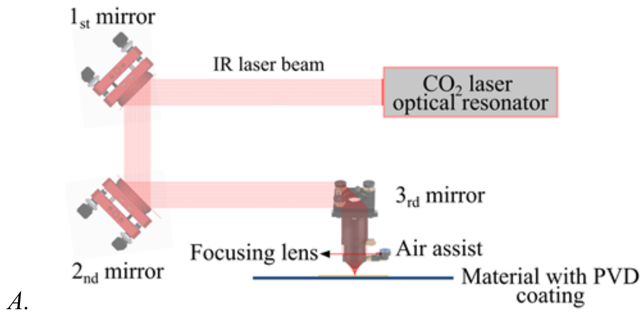

Fig. 2. Experimental set-up of carbon dioxide laser heat treatment of physical vapor deposited (PVD) coating on textile.

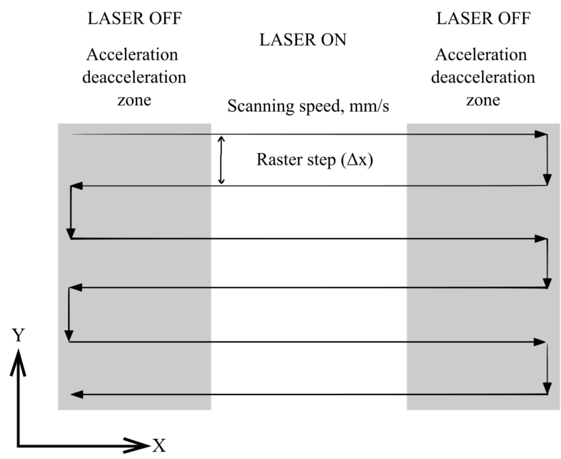

Fig. 3. Laser scanning path scheme

E. *Laser processing*

The laser scanning speed (v) remained constant at 100 mm/s for all laser-processed samples. The raster step was consistent at 100 µm across all samples, while the linear energy density (E) varied with values of 2.5 J/m, 5.1 J/m, and 7.1 J/m. Beam was focused on the samples with a focal point of approximately 80 micrometers and air assisted gas to the treatment area with pressure of 12 PSI and 90 liter per minute flow has been provided via nozzle.

F. *Peel-off tape adhesion test*

To assess the bond strength between the metallic coating and its base material e.g. fabric, we performed a 90-degree peel of test. This involved the use of 3M 610 permanent adhesive tape as described in reference [22]. Post-separation, the surface of the adhesive tape that was in contact with the metallized fabrics both laser treated and untreated was examined using confocal laser scanning microscope Olympus OLS5000, after the image software was used for analyzing the particles stuck to the tape via thresholding image by color and utilizing "particle count" tool whereas the summary results "%Area" was used to plot a graphs.

II. RESULTS AND DISCUSSIONS

The impact of CO_2 laser treatment on the adhesion of sputtered metals to textile substrates was investigated using peel-off tape adhesion tests. These tests quantified adhesive strength by measuring the percentage of metal remaining on the tape post laser treatment, with a higher percentage indicating weaker adhesion. Our analysis, depicted in Figures 4, 5, and 6, correlates average energy density (E, J/m) delivered to the metalized fabric with adhesive strength (Area, %), corresponding to fabrics A, B, and C described in Section 2 of this paper.

It should be noted that the "0" on the horizontal axis of the graphs indicates the percentage of the deposited coating area that peeled off of the fabric-metal combination without laser treatment applied.

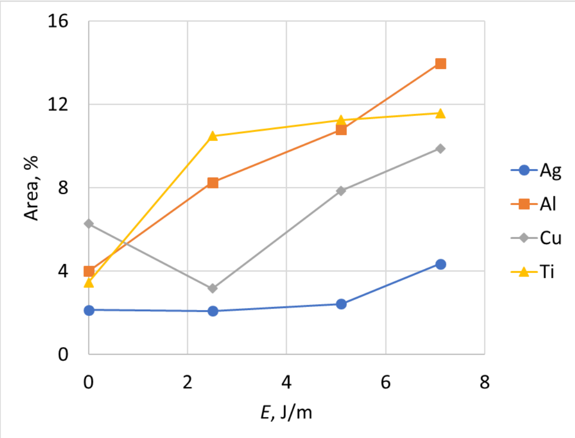

Fig.4. Peeled off adhesion test results of deposited metals on Fabric A dependent on laser linear energy density.

Across Al, Cu, Ag, and Ti, a general trend emerged: adhesion strength decreased with increasing linear energy density from 0 to 7.1 J/m. Contrary to expectations, no direct positive correlation was observed between delivered energy density and adhesive strength. Al exhibited a substantial increase in the percentage of metal remaining on the tape for fabric A, up to 3.5 times, fabric B up to 9.8 times, and fabric C up to 2.1 times, at an energy density of 7.1 J/m. Ag demonstrated enhanced adhesion over the range of linear energy densities, outperforming other metals, and did not exhibit the pronounced decline observed in Al.

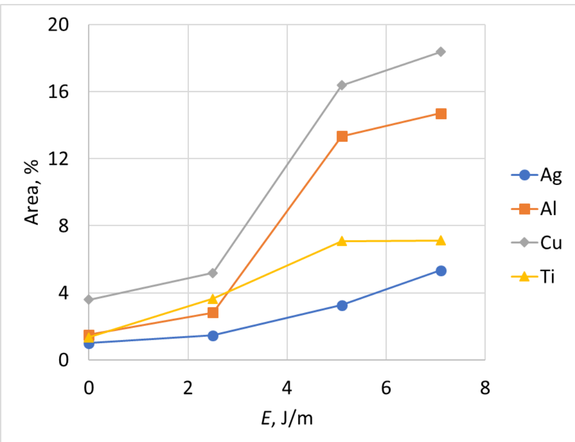

Fig.5. Peeled off adhesion test results of deposited metals on Fabric B dependent on laser linear energy density.

Cu showed increased adhesion at lower linear energy densities, almost 2 times for fabric A and almost 1.5 times for fabric C, but experienced a subsequent decrease as energy levels rose, similar to Al. Ti showed increased adhesion almost 1.9 times at lower linear energy density of 2.5 J/m for fabric C, but experienced a decrease at higher energy levels similar to other metals.

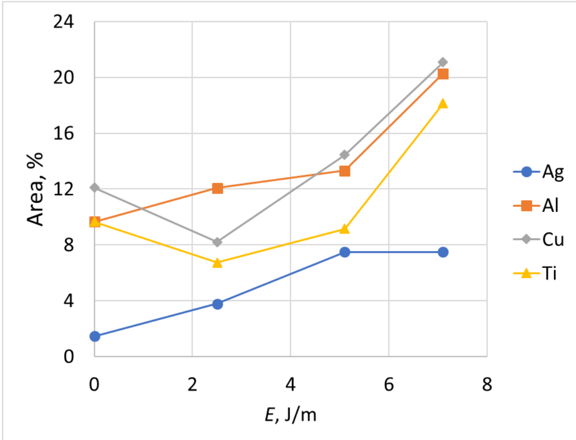

Fig.6. Peeled off adhesion test results of deposited metals on Fabric C dependent on laser linear energy density.

The reflective coefficient was hypothesized to be pivotal due to its influence on a metal's energy absorption at the laser's wavelength. However, an intricate balance is required as increased absorption beyond a certain threshold can induce thermal damage, reducing adhesive strength. The observed trends underscore the complex interplay between laser-induced thermal effects and the intrinsic properties of deposited metal layers. Overall, optimizing laser parameters is crucial to enhance adhesion without causing damage, emphasizing the need for further research in this area. Additionally, the differences in adhesion performance may also reflect variations in textile characteristics, sputtering conditions, and specific treatment procedures, highlighting the nuanced nature of sputtered metal-textile interactions and neednes for further research.

III. Conclusion

Our investigation into the adhesion characteristics of sputtered metals on functional textiles reveals a distinct dependency on laser linear energy density for each metal-textile combination.

For Fabric A, optimal adhesion for Ag and Cu is observed at 2.5 J/m, resulting in approximately 2% and 3% peel-off areas, respectively. Al and Ti exhibit decreasing adhesion percentages with increasing energy density.

Fabric B shows similar trends, with Ag peaking at 2.5 J/m with approximately 1.5% peel-off area. Al and Cu show increasing peel-off area percentages with rising energy density, while Ti displays better adhesion compared to Al and Cu.

Fabric C demonstrates increased peel-off area for Al and Ag with higher linear energy, whereas Cu and Ti exhibit smaller peel-off areas at a lower energy density of approximately 2.5 J/m.

These findings underscore the importance of identifying precise laser parameters values to optimize metal adhesion to textiles, crucial for composite material longevity and functionality. Future research should focus on determining exact energy thresholds and exploring the impact of laser parameters such as speed, raster step, focal spot, laser wavelength, repetition rate as well as impulse width on the metal-textile interface in an all-encompassing manner.

Overall, further studies could include better understanding via investigation of thermal treatment post metallized textile and impact on the textile fibers, as well as impact of different post sputtering treatment sources such as short and ultrashort impulse lasers as well as CAP plasma treatment.

IV. ACKNOWLEDGMENT

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