MULTI-OBJECTIVE PARAMETER OPTIMIZATION OF FABRIC ADHESIVE BONDING: A CASE STUDY OF PANEL BONDING

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DECLARATION

I declare that this is my own work, and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:2025.06.10

The above candidate has carried out research for the master's thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. J.R. Gamage

Signature of the Supervisor: Date: 10/06/2025

ACKNOWLEDGEMENT

Undertaking the writing of this thesis has been one of the most pivotal academic challenges I have encountered. The completion of this study would not have been possible without the dedicated support, remarkable patience, and insightful guidance of the professionals enumerated below.

First of all, I would be extremely grateful to **Dr. J.R.Gamage,** Senior Lecturer of the Department of Mechanical Engineering, University of Moratuwa, Who, despite his many other academic and professional engagements, committed to the role as my research supervisor, was a strength for me. I was inspired and motivated by his wisdom, knowledge, and commitment to the uppermost standards.

Finally, my sincere thanks to the **Mr.Dulanjana Tharindu** whose expertise in managing laboratory equipment was crucial for my experiments. Their patience and readiness to assist at all times have left a profound impact on the completion of my project.

ABSTRACT

Bonding strength and stretchability are two key parameters that define the quality of an adhesive-bonded fabric. However, there is a lack of studies on parameter optimization focusing on achieving multiple objectives. This study examines the optimization of adhesive bonding parameters in knitted fabric applications, focusing on achieving the highest bonding strength and stretchability. Four key process factors were analyzed using Taguchi experimental design. They are adhesive weight, distance between glue dot lines, press time, and curing time. The research aimed to identify the optimal levels for these factors to maximize the performance of polyurethane-based reactive hot melt adhesives (PUR).

The experimentation was conducted using an L27 orthogonal array. The bonding strength and stretchability were analyzed through the application of signal-to-noise (S/N) ratios, general Linear model, and ANOVA. The analysis discovered different optimum values for each factor when strength and stretchability were considered separately. The S/N ratios for both responses were normalized, and a composite S/N ratio was calculated.

The results reveal the optimum process parameters for achieving a balanced adhesive bond for the selected parameters. The study highlights the importance of balancing process parameters to meet the practical requirements of the textile industry, ensuring both durability and flexibility in bonded fabrics. The findings contribute to the existing knowledge base of adhesive bonding in knitted textiles and provide practical recommendations for industrial applications.

Keywords: Adhesive bonding, Design of experiment, Taguchi method, PUR bonding

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
PUR	Polyurethane-based reactive hot melt adhesives
DOE	Design of Experiments
PCC	propylene carbonate
ANOVA	Analysis of Variance
SN ratio	signal-to-noise ratios
HB	higher the better
LB	Lower the better
GA	Genetic algorithms
DF	Degrees of freedom
Adj SS	adjusted sums of squares
Adj MS	adjusted mean squares
CAD	Computer-Aided Design
GSM	grams per square meter
MDI	Methylenediphenyl diisocyanate
DMDEE	dimorpholinodiethyl ether
PU	Polyurethane
PA	Polyamide
PO	Polyolefin

1. INTRODUCTION

Traditional stitching methods have long been the basic technique for fabric panel joining in the apparel industry; However, they are associated with significant challenges. A significant concern relates to the prominence of stitched seams, which often results in discomfort, especially in garments designed for close contact with the skin, such as activewear and undergarments [1]. The overlapping layers of fabric and thread result in raised seams that can cause irritation during wear. these thick seams can disrupt the aesthetic appeal of garments.

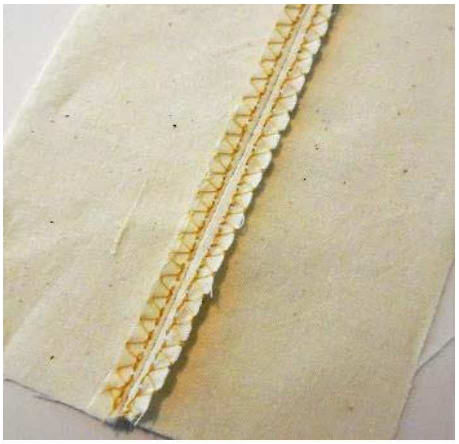


Figure 1:Traditional seam appearance

Bonding represents a modern technique that utilizes advanced adhesives to join fabric panels without the requirement for stitching. This method offers numerous benefits compared to traditional stitching, establishing it as a preferred choice across various applications [2]. One of the most significant benefits is the elimination of thick seams, resulting in a smoother, more comfortable finish. This feature is particularly valuable in garments where the fabric comes into direct contact with the skin.

1.1. Fabric Joining Technique

The methods of traditional stitching, adhesive bonding, and ultrasonic bonding serve as three common techniques for fabric joining, each exhibiting unique strengths and weaknesses. Traditional stitching relies on needle and thread to create seams, offering strong and durable connections. However, it can create puncture holes, weaken waterproof fabrics, and may cause discomfort due to seam bulk. Bonding, on the other hand, uses adhesives or heat to join fabrics without needle penetration. This method enhances fabric flexibility, provides a smooth finish, and maintains waterproofing. It also reduces seam irritation, making it ideal for sportswear, lingerie, and high-performance textiles. However, bonding requires specific adhesives and processing conditions, which can increase manufacturing costs. Ultrasonic bonding constitutes a modern technique that utilizes high-frequency vibrations to melt and fuse thermoplastic-based fabrics. It is fast, precise, and eliminates the need for thread or adhesives, making it ideal for medical and disposable textiles. However, its effectiveness is limited to synthetic materials and requires specialized equipment [20].

Table 1: Comparison of traditional stitching, bonding, and ultrasonic bonding

Feature	**Traditional Stitching Seams**	**Bonding**	**Ultrasonic Bonding**
Bonding Method	Needle and thread interlocking	Adhesives applied and cured with heat/pressure	High-frequency ultrasonic vibrations create localized heat
Flexibility & Comfort	May cause fabric stiffness or irritation due to thread	Soft and seamless, enhances wearer comfort	Seamless and flexible, but may be slightly stiff
Aesthetic Appearance	Visible stitches, potential puckering	Seamless and smooth finish	Seamless but with a visible weld line
Material Compatibility	Works with most fabrics	Works with most fabrics	Best for synthetic fabrics, limited for natural fibers
Durability in Washing	50 - 100 (depending on thread quality and fabric type	20 - 150 (depending on adhesive type and fabric compatibility)	20 – 50

Among these methods, bonding is the most suitable choice for many modern applications due to its superior comfort, seamless appearance, waterproofing capabilities, and compatibility with stretch fabrics. Although traditional sewing methodologies are often preferred due to their durability and cost-effectiveness, and ultrasonic bonding exhibits advantages in terms of speed and ecological sustainability, adhesive bonding provides an ideal balance of strength, versatility, and aesthetic quality, making it especially suitable for industries such as fashion, sportswear, and outdoor gear.

1.2. Aim and Objectives

The aim of this research is “to identify and optimize the key process parameters of fabric adhesive bonding to achieve the highest levels of bond strength and stretchability”

The following four objectives are set to achieve the aim of the research.

1. To understand the chemical composition of adhesives and identify process parameters affecting the bond's strength and stretchability.
2. To evaluate the impact of process parameters and determine the optimal combination for maximum strength and stretchability.
3. To formulate prediction models for each input parameter to determine their effects on the adhesive bonding performance.
4. To validate the predictive models using experimental data to ensure accuracy and reliability in estimating adhesive bond performance.

2. LITERATURE REVIEW

2.1. Fabric Bonding Techniques

Thermoplastic and thermosetting bonding represent two distinct categories of fabric bonding methodologies. Thermoplastic bonding refers to adhesives that soften under heat and solidify upon cooling, thus allowing for reactivation multiple times. These adhesives are frequently employed in textile applications due to their advantageous flexibility. Examples of thermoplastic adhesives incorporate polyurethane (PU), polyamide (PA), and polyolefin (PO) adhesives, which are usually applied in the form of hot melt adhesives, films, or webs.

Thermoplastic adhesives are ideal for bonding fabrics where elasticity and reworkability are important. However, their thermal resistance is limited, as they demonstrate a propensity to soften when exposed to elevated temperatures, thus making them less suitable for extreme environmental conditions [3] [4].

Thermosetting adhesives consist of substances that undergo a chemical curing mechanism, resulting in the creation of permanent cross-linkages that cannot be reversed upon exposure to high temperatures. Once cured, thermosetting adhesives form strong, durable bonds that resist high temperatures, chemicals, and environmental exposure. Examples include reactive polyurethane-based hot melt adhesives (PUR) and some epoxy-based adhesives Unlike thermoplastic adhesives, thermosetting adhesives do not exhibit softening when subjected to elevated temperatures, thus making them exceptionally appropriate for high-performance applications requiring long-term stability. However, their irreversible nature means that bonded materials cannot be reprocessed or adjusted after curing [2].

2.1.1 Comparison of Fabric Bonding Techniques

The table provides a detail analysis of different types of adhesives used in textile bonding, categorized into thermoplastic and thermosetting adhesives. Thermoplastic adhesives, including Polyurethane (PU), Polyamide (PA), Polyolefin (PO), and Silicone adhesives, shows a various range of flexibility, tensile strength, and durability [5] [4].

Table 2: Comparison of fabric bonding techniques

	Thermoplastics			**Thermosetting**	
Feature	PU Adhesives	PA Adhesives	PO Adhesives	Silicone Adhesives	PUR Adhesives
Durability & Wash Resistance	40 - 80	50 - 100	30 - 60	20 - 50	80 – 150
Flexibility & Comfortability	Soft and flexible, maintains fabric drape	Moderate flexibility but slightly stiff	Flexible, soft feel	Highly flexible and soft	High flexibility and soft texture
Heat & Chemical Resistance	Good, resists mild heat and chemicals	Excellent, high-temperature resistance	Good, but weaker under high heat	Excellent, withstands extreme temperatures and chemicals	Excellent, very strong against heat and solvents
Material Compatibility	Bonds well to most fabrics and synthetics	Bonds well to synthetic fabrics	Limited materials	Limited materials	wide range of materials
Cost	$2.4	$2.5	$2.70	$1.20	$0.60

PU-based reactive hot melt adhesives demonstrate superior performance compared to other adhesive varieties due to their enhanced bonding strength, prolonged durability, and capacity to endure extreme environmental conditions. Unlike traditional PU, PA, PO, and silicone adhesives, PUR adhesives continue to cure after application, increasing their strength over time. This unique property ensures long-lasting bonds that remain strong even after repeated washing, stretching, and exposure to chemicals [6].

Another key advantage of PUR adhesives is their high flexibility and comfort, making them ideal for applications where fabric movement is essential. Unlike PA adhesives, which can be rigid, PUR adhesives maintain the soft and stretchable nature of fabrics, enhancing wearer comfort in performance wear and medical textiles. Their seamless bonding method also eliminates the need for stitching, reducing irritation and bulk in garments [1].

PUR adhesives also excel in waterproofing and heat resistance, offering protection up to 150°C and withstanding over 100 wash cycles. In comparison, PU and PO adhesives provide lower heat resistance, while silicone adhesives, although highly resistant to heat and UV, lack strong bonding strength. The ability of PUR adhesive to bond with a wide variety of substrates, including both synthetic and natural fibers, considerably enhances their multifunctional properties, thus making them suitable for a broader range of applications [3].

2.2. Polyurethane-Based Reactive Hot Melt Adhesives

Polyurethane-based reactive hot melt adhesives (PUR) are advanced adhesives widely utilized across multiple industries due to their excellent bonding strength, adaptability and durability. Derived from isocyanate-terminated urethane prepolymers, PUR offer a versatile bonding solution characterized by their moisture-curing capability, which transforms them into high-performance cross-linked polymers. PURs are applied as adhesive in molten stage, cooled to solidify and can be subsequently cured through the reaction of the isocyanate groups and ambient moisture [3].

On the other hand, polyurethane based reactive hot melt adhesives have progressively become the common favorite for fabric bonding due to the following reasons. PURs are famous for the formation of rigid structures that, however, have very good adaptability to changes and stresses [7]. The mechanism of curing through the presence of moisture makes PURs ideal in bonding with the ability to provide early bond strength and increasing the cure strength for long-lasting applications depending on the environmental conditions [8]. However, it is important to note that PURs generally have good adhesion to a variety of substrates and can be used on different fabrics, polymers, metal or other composite materials as the need may be [3].

In addition, the crosse linked structure of PURs bring out good thermal stability and resistance towards deterioration to make them acceptable for use in internal and outdoor uses [4]. Another advantage is the low application temperature of PURs that makes the energy consumption limited and even reduces the probability of thermal degradation of the substrate materials such as textiles [5].

Since PURs are known to have very good process characteristics, are highly recommended in the textile industry and are particularly well-suited to fabric bonding, the following process parameters which are relevant to the application of PURs shall be the focal point of this study. It is the intention of this study to look at the opportunity for betterment of executive PUR adhesive bonding and ultimately the field of adhesive bonding for textile and manufacturing industries.

2.2.1. Composition and Synthesis of PUR

The isocyanate-terminated PUR prepolymers were synthesized by the reaction between a polyol or polyol blends and an excess of Methylenediphenyl diisocyanate (MDI). The synthesis molar ratio of NCO to OH groups was 1.4:1 and theoretical isocyanate content value (NCO wt%) was 2.5. The PUR prepolymers synthesis was carried out in a round-bottomed, four-necked liter flask equipped with a mechanical stirrer, a heating mantle and a thermometer. In the prepolymerization process, a selected polyol or polyol blends was added to the reactor and heating to 115 ± 5°C under a vacuum of less than 1 mm Hg for 1 h to remove the residual water. MDI was melted at 50°C and used after excluding white MDI dimer precipitates in the melt (17). After that, MDI and dimorpholinodiethyl ether(DMDEE) were added sequentially into the reactor and stirred for 1.5 h at 115 ± 5°C until the desired NCO wt% was obtained [6] [3]

The major reactive element in PUR is the isocyanate group (-NCO), which reacts with ambient moisture to form carbamic acid. This intermediate decomposes into an amine, which subsequently reacts with additional isocyanate groups to form urea linkages. This curing process results in a dense, cross-linked network that imparts superior mechanical and adhesive properties [6] [3] [7]

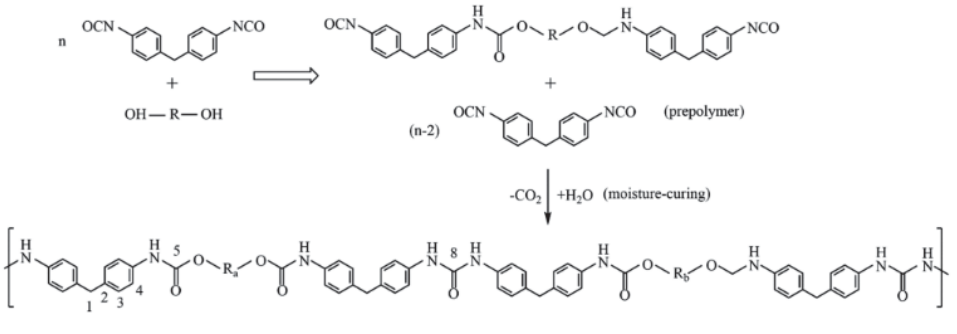


Figure 2 - Scheme for the synthesis and moisture curing processes of PUR

2.2.2. Properties of PUR

PUR demonstrates significant tensile strength and flexibility, making them appropriate for a diverse range of applications. For instance, PUR exhibits superior mechanical strength and adhesive properties in comparison to conventional petrochemical-based adhesives, which is chiefly due to their crystalline structure and reduced phase segregation between the rigid and flexible segments [5].

PUR maintains thermal stability up to 270°C, exhibiting three distinct stages of decomposition that correspond to breakdown of polycarbonate units, urethane bonds, and polyester/polyether units. This is suitable for high temperature applications [3]

Moisture breathability and hydrophilicity can be modified through the careful selection of polymer types. The high-water vapor transmission rates associated with PPC-based PUR establish their ideal application in breathable coatings for textiles. Similarly, bio-PTMEG-based PUR are hydrophobic, offering excellent resistance to hydrolytic degradation [5].

PUR is effective in bonding diverse substrates, including metals (aluminum, steel), plastics (polycarbonate), and textiles. For instance, PPC-based PUR has exhibited superior bonding strength when compared to conventional adhesives in single-lap shear tests involving stainless steel and polycarbonate [4].

2.2.3. Benefits of Polyurethane-Based Reactive Hot Melt Adhesive

Polyurethane-based reactive hot melt adhesives (PURs) present unique benefits over other bonding techniques, making them a suitable selection in many industrial applications. One of their key benefits is their ability to grant strong, flexible bonds that can withstand dynamic stresses. Unlike traditional stitching, which makes localized stress points, PUR adhesives distribute stress uniformly across the bonded surface, improving durability.

PUR adhesives appropriate with a wide range of materials, including different fabric types, polymers, metals, and composites. This behavior allows manufacturers to explore innovative design options without being constrained by material compatibility issues. Additionally, the moisture-curing mechanism of PUR adhesives ensures rapid initial bonding and long-term strength as the adhesive fully cures [3].

PUR adhesives applications have requirement of resistance to environmental factors such as moisture, heat, and chemicals. Their cross-linked structure, established during the curing process, imparts significant thermal stability and resistance to deterioration, Making them suitable for both internal and external applications. Furthermore, their low application temperature reduces the energy consumption and reduces the risk of thermal damage to sensitive materials [7].

Finally, PUR adhesives support seamless and lightweight designs, contributing to improved comfort and aesthetic appeal in textiles and enabling weight reduction in industries like aerospace, Sport ware. These features effect polyurethane-based reactive hot melt adhesives a foundation of modern adhesive bonding technology [3]

PURs also provide ease in the aspect of design. The fact that it does not require seams also gives the advantage of furniture and structure when integrated into fashionable and light clothing in fashion hence improving its comfort value. This is especially true when it comes to sportswear and medical textiles, because comfort is the main value in this kind of products [4]. In conclusion therefore, owing to good bonding characteristics, versatility, moisture resistance and enhanced flexibility, polyurethane based reactive hot melt adhesives should be thought of frequently when it comes to selection of an adhesive for the industrial application especially those related to textile and manufacturing industries.

2.3. Enhancement of PUR adhesive properties in other researches

Improving the strength of PUR adhesives involves optimizing their chemical composition and structural properties. Recent research has focused on enhancing the initial adhesion performance, mechanical strength, and environmental sustainability of these adhesives. By incorporating bio-based materials, modifying molecular structures, and utilizing advanced bonding techniques, significant improvements in adhesive strength and performance have been achieved. The following sections detail various strategies and findings from recent studies.

2.3.1. Use of Bio-Based Polyols

Replacing traditional petroleum-based polyols with bio-based polycarbonate polyols has shown to improve the flexibility and green strength of PUR. This substitution not only enhances the adhesive's performance but also aligns with sustainability goals by increasing the biogenic carbon content of the adhesive [8]

The incorporation of thermoplastic polyurethane (TPU) in small proportions (10-15 wt.%) further enhances the initial adhesion and green strength without compromising flexibility. However, higher TPU content can lead to increased crystallinity, which may reduce flexibility [9]

2.3.2. Molecular Design and Structural Modifications

The introduction of supramolecular motifs, such as ureidopyrimidinone (UPy), into the polyurethane structure can significantly enhance shear strength and impact resistance. These motifs facilitate the formation of quadruple hydrogen bonds, which improve energy dissipation and adhesion under high-stress conditions [10]

Utilizing chain extenders with multiple hydrogen-bonding capabilities, such as furandicarboxamide, can improve the elongation at break and breaking strength of the adhesive. This results in ultrahigh adhesive strength across various substrates [8]

2.3.3. Cross-Linking and Dynamic Bonding

The use of crosslinking agents in polyurethane hot melt adhesive films can enhance final adhesion strength and water resistance. However, this may also lead to a decrease in tensile stress and elongation at break, indicating a trade-off between adhesion and flexibility [11]

Dynamic oxime-carbamate bonds have been introduced to create a three-dimensional cross-linked network, providing high initial and ultimate adhesion strength. This structure allows for efficient bonding-debonding cycles, enhancing the adhesive's recyclability and durability [11].

2.3.4. Optimization of Diol Components

Blending polyester and polycarbonate diols in the adhesive formulation can balance bonding properties, tensile strength, and heat resistance. Increasing the molecular weight of certain diols, such as sebacic acid-based polyester diols, has been shown to improve mechanical properties and lap shear strength [12]

2.3.5. High-Temperature Resistance Techniques

A method involving the use of silane modifiers and dehydrated components in the synthesis process has been developed to improve the high-temperature resistance and overall mechanical properties of polyurethane hot melt adhesives. This approach enhances the adhesive's performance under extreme conditions, such as cold and heat shock resistance [8].

While these strategies have demonstrated significant improvements in the strength and performance of polyurethane-based reactive hot melt adhesives, it is important to consider the potential trade-offs between different properties, such as flexibility and adhesion strength. Additionally, the environmental impact of these adhesives remains a critical consideration, with ongoing research focusing on increasing the use of renewable materials and reducing the carbon footprint of adhesive formulations.

2.4. Factors Affecting PUR Bonding Strength and Stretchability

PUR bonding has become extensively utilized in industrial and consumer sectors achieve their significant adhesion strength, flexibility, and ability to adapt to various substrates [6]. Achieving optimal effectiveness in terms of tensile strength and stretchability requires a thorough understanding of the factors that influence these characteristics. This chapter examines the essential factors that affect the bonding strength and stretchability of polyurethane (PUR), including material composition, processing parameters, and environmental conditions.

2.4.1. Polymer Composition

Polyols

Polyols form the soft segment of PUR adhesives, influencing their flexibility and stretchability. Variations in molecular weight, hydroxyl functionality, and chemical structure impact the adhesive’s mechanical properties: [6]

- High-Molecular: Weight Polyols: Enhance flexibility and stretchability.
- Bio-Based Polyols: Improve sustainability while maintaining performance.

Diisocyanates

Diisocyanates are the hard segment contributors, controlling the adhesive’s strength and rigidity. Commonly used diisocyanates include [6]:

- Methylene Diphenyl Diisocyanate: Balances strength and flexibility.
- Toluene Diisocyanate: Provides high bonding strength but may reduce flexibility.

2.4.2. Application Parameters

The application and curing process highly affect the bonding strength and stretchability of PUR adhesives. Critical parameters include:

Adhesive Weight

The weight and distribution of adhesive dots determine the uniformity of the bond and its mechanical properties [3]:

- Higher Weight: Increases bonding strength but may reduce stretchability.
- Uniform Distribution: Ensures consistent stress distribution across the bonded surface.

Adhesive penetration

Press time influences the initial hold and the uniformity of the adhesive spread:

- Shorter penetration: May lead to incomplete bonding.
- Optimal penetration: Enhances contact and adhesion, improving overall performance.

Curing Time

Curing time determines the extent of crosslinking in the adhesive [6]:

- Under-Curing: Reduces bond strength and durability.
- Over-Curing: May increase strength, brittleness, reducing stretchability

Application Temperature

The application temperature affects the viscosity and flow of the adhesive [7]:

- High Temperature: Improves flowability and wetting but may degrade thermal-sensitive substrates.
- Low Temperature: Preserves substrate integrity but may hinder proper bonding.

2.4.3. Environmental Conditions

Environmental factors during and after bonding impact the long-term performance of PUR adhesives. These include:

Humidity

PUR adhesives rely on moisture-curing mechanisms. The availability of ambient moisture affects curing time and bond strength [7]:

- High Humidity: Accelerates curing but may trap moisture, causing defects.
- Low Humidity: Slows curing, potentially leading to incomplete bonds.

Room Temperature

Thermal conditions influence the adhesive's mechanical properties:

- High Operating Temperatures: May cause thermal degradation.
- Low Operating Temperatures: Reduce flexibility and stretchability.

2.5. Applications of adhesive bonding in other Industrial Sectors

Footwear Industry

PUR have been widely adopted in the footwear industry for their high adhesion strength and durability. A study on sustainable PUR based on biobased polyols demonstrated their suitability for footwear applications, with adhesion properties comparable to traditional adhesives [13]. Another study on eco-friendly PUR derived from vegetable oils highlighted their potential to replace solvent-based adhesives, reducing VOC emissions and improving sustainability [10]

Wood Industry

In the wood industry, PURs are used for edge sealing and bonding wood veneer. A study on reactive polyurethane hot melt adhesives for edge sealing demonstrated their high initial and final bonding strength, as well as their heat resistance and storage stability. Another study on aluminum and wood veneer bonding highlighted the versatility of PUR in bonding different substrates, with applications in furniture and construction materials [3]

Automotive and Construction Sectors

The automotive and construction sectors have also benefited from the use of PURs. A study on PPC-based PURs demonstrated their suitability for bonding metals and plastics, with applications in vehicle manufacturing and construction materials. Another study on dual-curing PURs highlighted their potential for use in high-end electronics and smart devices, where rapid assembly and high performance are required [8]

Textile and Packaging Industries

In the textile and packaging industries, PURs are used for their high adhesion strength and flexibility. A study on furandicarboxamide-based PURs demonstrated their ultrahigh adhesive strength on various substrates, including metals, composites, and plastics. Another study on vegetable oil-based PURs highlighted their potential for use in packaging materials, offering a sustainable and high-performance alternative to traditional adhesives [8]

2.6. Research Gap

Adhesive bonding techniques are an important focus area of study that has grown significantly in the advancing discipline of materials science and engineering, especially in applications that call for strength and elasticity. Despite greater improvements in adhesive technological systems and advanced optimization techniques, there are some gaps left open. Such gaps afford innovative research for solving unknown issues and improving the existing practices in the field.

The literature work being done in this particular area of adhesive bonding is equally and mainly centered on the formulation of higher types of adhesives. Specifically, there is a lack of research efforts in achieving multiple objectives of fabric knitted strength and stretchability at the same time. Previous studies have mostly targeted the use of bio-based and CO2-derived polyols and the alteration of chemical contents of epoxy adhesive for increasing its strength and environmental endurance. Also, most of the previous studies have paid more attention to the composition of the adhesive rather than to process parameters. Among the bonding parameters have quite an effect on the bond strength and flexibility; however, they have not been studied systematically.

Secondly, most optimization research have tackled the matter from the aspect of a single parameter, such as increasing the bond strength or reducing curing time or making it less susceptible to the environmental conditions. These investigations are very helpful, although they do not take into account multiple objectives, which should be considered to obtain the right balance between stiffness and adaptability of the bonded materials.

These findings indicate that there is a gap in research to have a synergetic approach to adhesive bonding optimization. In this context, addressing this gap can benefit the advancement of the subject of adhesive bonding in the future, with a focus on developing new applications for high performance in knitted fabrics. The application of the multi-objective optimization in combination with design of experiment methods may offer great potential in obtaining the balance between bonding strength as well as stretchability to meet the practical application of the textile industry.

3. RESEARCH METHODOLOGY

3.1. Overview Of Methods Used

To achieve the research objectives, a combination of qualitative and quantitative methods will be employed. The study begins with a comprehensive literature review, which will be conducted using thematic coding. This method involves identifying key themes, trends, and gaps in existing research related to fabric adhesive bonding. Thematic coding will allow for a structured synthesis of prior studies, helping to establish a foundation for experimental design and optimization techniques.

The next phase involves experimental design and analysis to determine the optimal combination of parameters for maximum strength and stretchability. The Design of Experiments (DOE) approach will be utilized to systematically plan and execute experiments, ensuring efficient data collection while minimizing variability. Signal-to-Noise (S/N) ratio analysis will be used to evaluate the robustness of different parameter settings, while Analysis of Variance (ANOVA) will identify the statistical significance of each input factor. Additionally, residual plots will be analyzed to verify the assumptions of the statistical models and assess data normality and homoscedasticity. To address the multi-objective nature of the study, multi-objective optimization techniques will be applied to find the best trade-off between strength and stretchability.

Finally, prediction models will be developed to quantify the effects of each input parameter on adhesive bonding performance. This will be achieved using the regression equation method, which will allow for the formulation of mathematical models that describe the relationship between input factors and bonding performance. These models will provide insights into how different process parameters influence adhesion strength and stretchability, ultimately facilitating the prediction and optimization of adhesive bonding conditions

Table 3- Mapping of objectives and methods

	Objectives	**Methods**
Objective 1	Conduct a comprehensive Literature review	Thematic coding and analysis
Objective 2	Design and perform experiments to determine the optimal combination for maximum strength and stretchability	Design of experiment (DOE), Analysis (S/N Ratio Analysis, ANOVA, Residual Plots), Multi-objective optimization
Objective 3	Formulate separate prediction models for each input parameter to determine their effects on the adhesive bonding performance.	Regression equations

3.2. Method of literature Review (Objective 1)

The keywords "Adhesive bonding, Design of experiment, Taguchi Method, PUR bonding" were searched in the title and abstract on the IEEE Explore, Google Scholar and Science Direct. Only peer-reviewed journals were chosen for this literature review as they can be traced on scientific databases. Literature published in the last 10 years (2014 to 2024) in the English language were considered for this review.

183 research papers were found related to these keywords. Next, the abstracts of the 183 records were critically reviewed and 62 papers were chosen for detailed review of the full text. The selection protocol in the full text review phase was literature focused on fabric bonding techniques, Chemical composition of PUR bonding, factors

affecting the strength of PUR bonding, design of experiment, testing method of strength and stretchability of bond. The method of review is illustrated in Figure 3 below. 40 studies were included in this literature review.

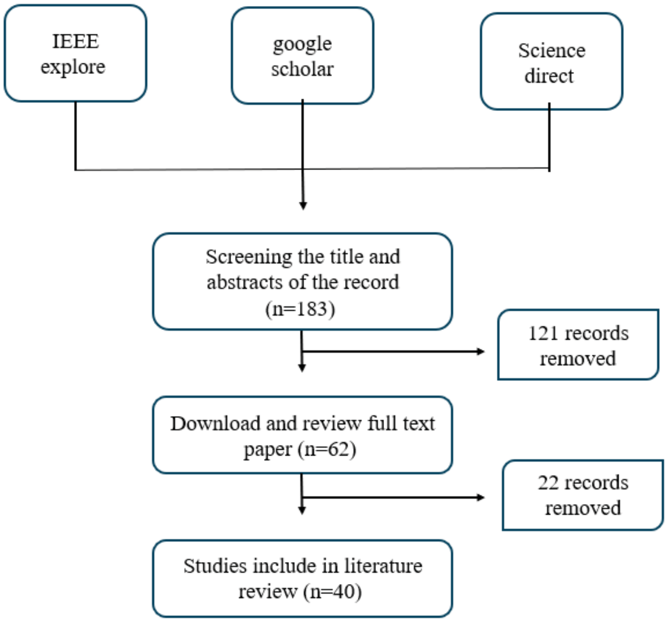
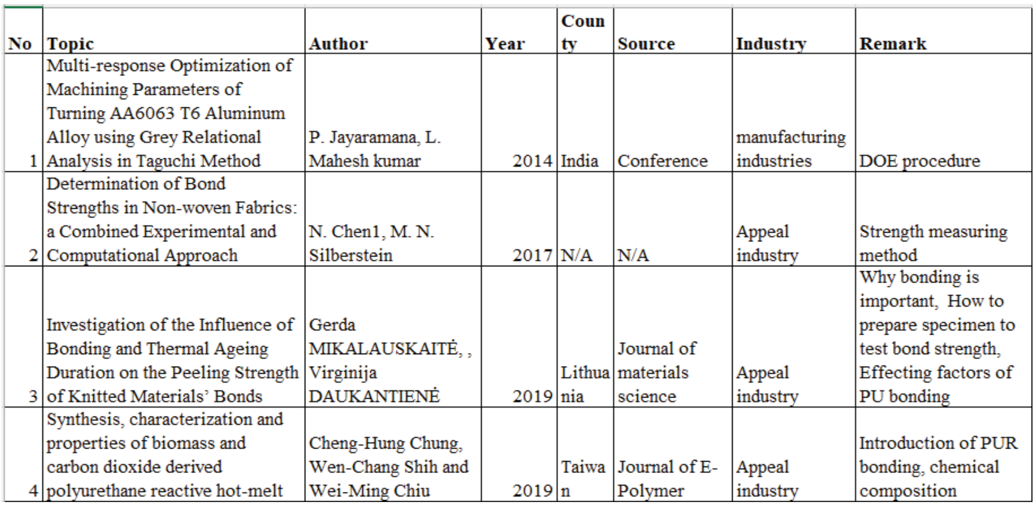


Figure 3:Overview of shortlisting the articles for review

Thematic coding is a technique commonly used in literature review, especially qualitative research, to analyze and organize the content of research papers, articles, and other material. It helps to identify and group the repeating themes or patterns in the literature review. Topics of Thematic codes of this review are topic, Author, publish year, industry, and content. Data of thematic coding is presented in table 4.

Table 4: A summary view of thematic coding table



No	Topic	Author	Year	County	Source	Industry	Remark
1	Multi-response Optimization of Machining Parameters of Turning AA6063 T6 Aluminum Alloy using Grey Relational Analysis in Taguchi Method	P. Jayaramana, L. Mahesh kumar	2014	India	Conference	manufacturing industries	DOE procedure
2	Determination of Bond Strengths in Non-woven Fabrics: a Combined Experimental and Computational Approach	N. Chen1, M. N. Silberstein	2017	N/A	N/A	Appeal industry	Strength measuring method
3	Investigation of the Influence of Bonding and Thermal Ageing Duration on the Peeling Strength of Knitted Materials' Bonds	Gerda MIKALAUSKAITĖ, , Virginija DAUKANTIENĖ	2019	Lithuania	Journal of materials science	Appeal industry	Why bonding is important, How to prepare specimen to test bond strength, Effecting factors of PU bonding
4	Synthesis, characterization and properties of biomass and carbon dioxide derived polyurethane reactive hot-melt	Cheng-Hung Chung, Wen-Chang Shih and Wei-Ming Chiu	2019	Taiwan	Journal of E-Polymer	Appeal industry	Introduction of PUR bonding, chemical composition

The distribution of publication year is especially important in a literature review. It shows the breadth, reliability, and depth of analysis. The distribution of the number of publications is presented in Figure 4.

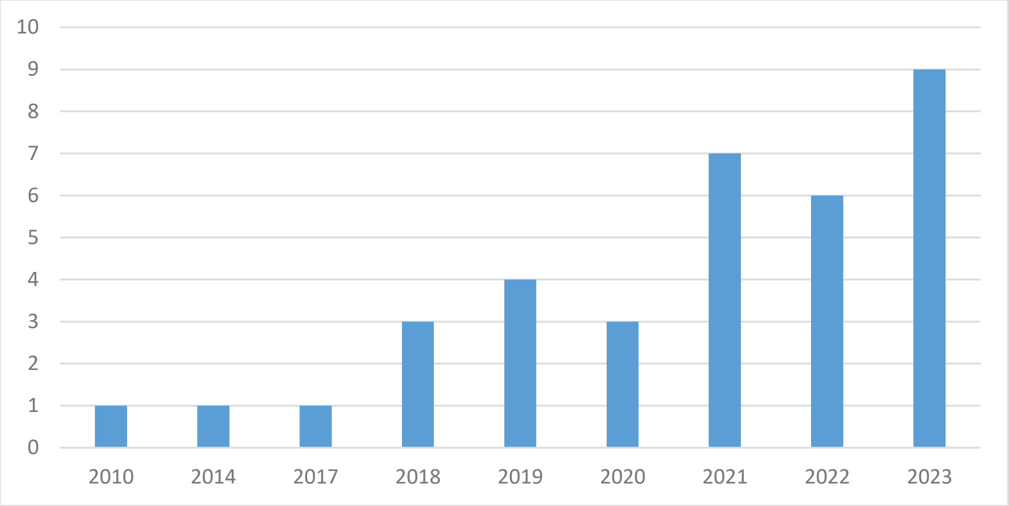


Figure 4: Distribution of publication year

Journal articles are extremely important in literature reviews because of their peer review rigor, latest information, references, academic authority, and methodological information. It improves credibility and precision also. Below mentions the mostly referred journals for this study.

- Journal of materials science
- Journal of E-Polymer
- Journal of Gas Science and Engineering
- Journal of Advances in Industrial and Manufacturing Engineering
- Journal of Optics and Laser Technology
- Journal of cleaner Engineering and Technology
- Journal of material science and technology
- Journal of Materials Research and Technology
- Journal of Results in Engineering

The geographical distribution of the studies chosen for this study are illustrated in Figure 5. Most of the literature were from a Chinese context while a considerable portion came India and France. China although classified a developing country is a special case as it is a highly industrialized country. Overall, geographical distribution provides this study with a good mix of studies from both developed and emerging economies.

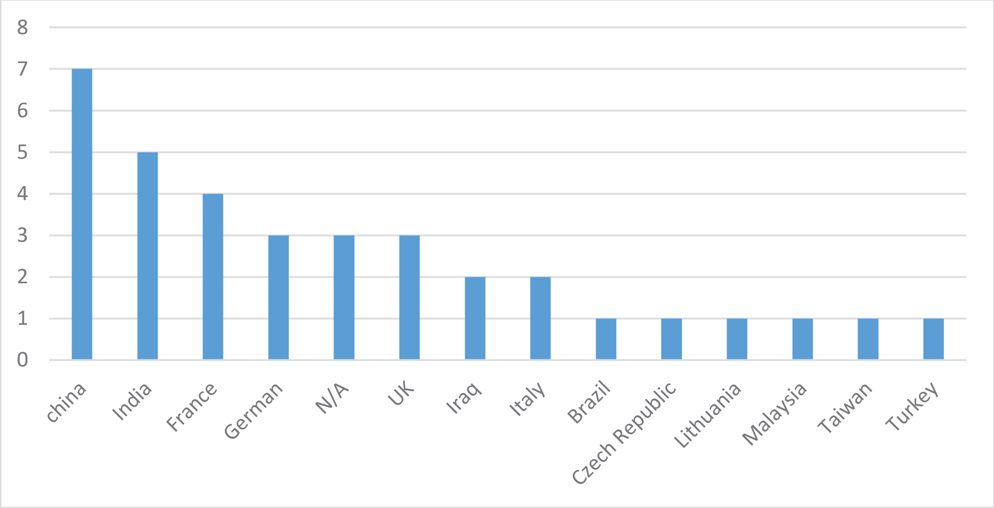


Figure 5: Geographical distribution of the studies

3.3. Optimization Procedures Used in Other Research (Objective 2)

This section will briefly introduce the major categories of DoE most suitable to the optimization of adhesive bonding parameters. Specific steps on how the DoE approach will be implemented will be described in the Research Methodology chapter.

Full Factorial Designs

The full factorial method is an overall experimental design that is very comprehensive. It entails the examination of all the treatment factors and their levels. This method gives general information on the main effects and interaction of all factors [6] [7].

Taguchi Method

The Taguchi method is an excellent method applicable for enhancing quality of any product or process. It places heavy reliance on orthogonal arrays as a way of studying several factors in a number of experiments done in a minimal number of trials [8].

Multi Objective Optimization

The multi-objective parameter optimization on the other hand is an organized process of searching for the optimal solution among different objectives that are involved in a certain system or process. Various approaches for MO optimization including weighted sum method and pareto frontier exploration are explained [3], [4] [5].

As presented in the Literature Review chapter of this work, the reader will be able to get a wider perspective of design of experiments, as well as determine its applicability within the improvement of adhesive bonding parameters. It is then appropriate that the specifics can be described in detail in the Research Methodology section.

3.3.1. Full Factorial Designs

The full factorial method is one of the most comprehensive experimental designs. It involves testing all possible combinations of factors and their levels. This method provides detailed insights into the main effects and interactions of all factors [14].

3.3.1.1. Steps in Full Factorial Design

- Define the Objective: Clearly state the purpose of the experiment, such as optimizing a process or identifying significant factors.
- Identify Factors and Levels: Select the input factors (independent variables) to be studied and define their levels. For example, if there are three factors (A, B, and C) with two levels each (low and high), then the number of combinations is [15].

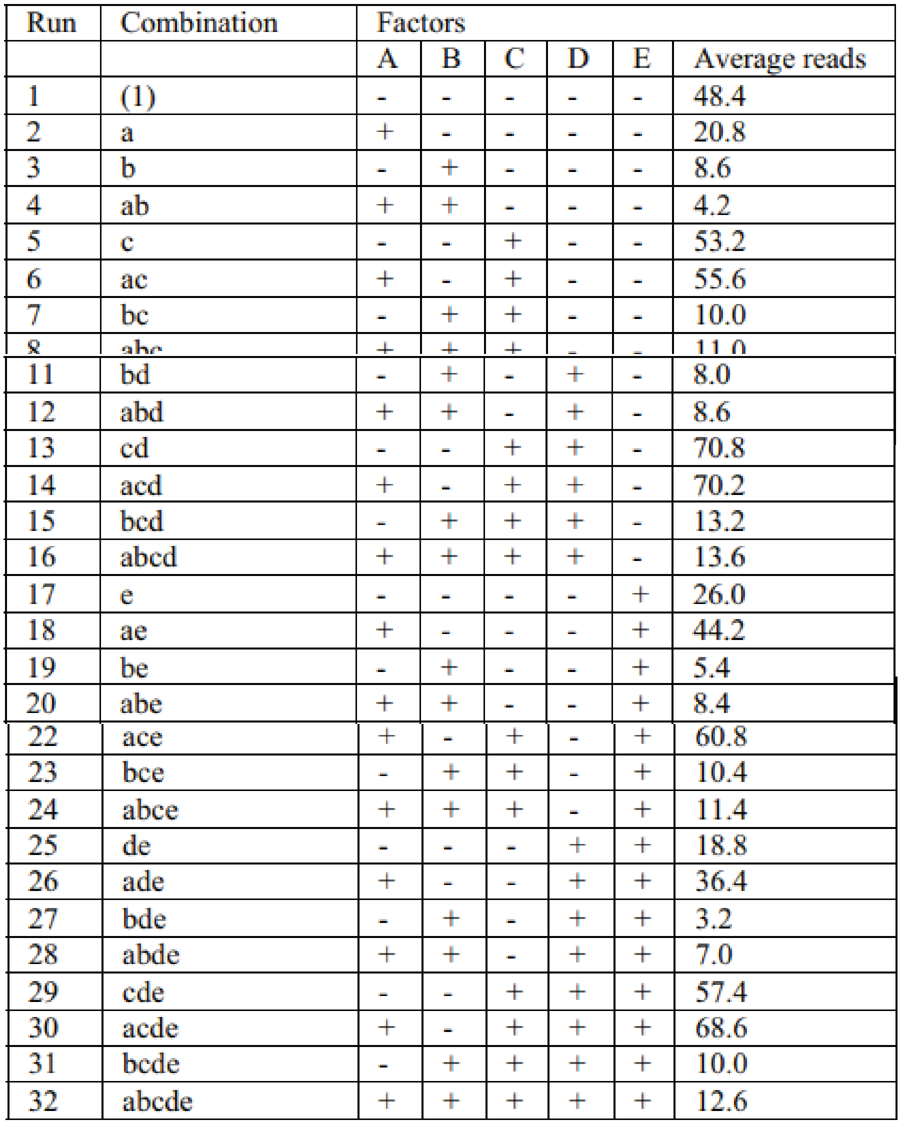
Table 5- Example of factors and Its Levels [15]

Factors	Designation	Low(-)	High(+)
Distance from tag to antenna (in.)	A	2	12
Speed of conveyor belt (ft/min.)	B	10	50
Tag Type	C	Avery Dennison	Alien Squiggle
Tag orientation	D	Horizontal	Vertical
Tag placement	E	On package facing antenna	On top of the package

- Create Experimental Runs: List all possible combinations of factor levels. For factors with levels each, the total number of experimental runs is calculated as:

- Randomize the Order: Randomize the sequence of experimental runs to reduce bias caused by extraneous variables.
- Conduct the Experiments: Perform the experiments as per the defined combinations, ensuring consistency in measurements.

Table 6- Example of experiment trials [15]



Run	Combination	Factors					
		A	B	C	D	E	Average reads
1	(1)	-	-	-	-	-	48.4
2	a	+	-	-	-	-	20.8
3	b	-	+	-	-	-	8.6
4	ab	+	+	-	-	-	4.2
5	c	-	-	+	-	-	53.2
6	ac	+	-	+	-	-	55.6
7	bc	-	+	+	-	-	10.0
8	abc	+	+	+	-	-	11.0
11	bd	-	+	-	+	-	8.0
12	abd	+	+	-	+	-	8.6
13	cd	-	-	+	+	-	70.8
14	acd	+	-	+	+	-	70.2
15	bcd	-	+	+	+	-	13.2
16	abcd	+	+	+	+	-	13.6
17	e	-	-	-	-	+	26.0
18	ae	+	-	-	-	+	44.2
19	be	-	+	-	-	+	5.4
20	abe	+	+	-	-	+	8.4
22	ace	+	-	+	-	+	60.8
23	bce	-	+	+	-	+	10.4
24	abce	+	+	+	-	+	11.4
25	de	-	-	-	+	+	18.8
26	ade	+	-	-	+	+	36.4
27	bde	-	+	-	+	+	3.2
28	abde	+	+	-	+	+	7.0
29	cde	-	-	+	+	+	57.4
30	acde	+	-	+	+	+	68.6
31	bcde	-	+	+	+	+	10.0
32	abcde	+	+	+	+	+	12.6

- Analyze the Results: The significance of each variable will be decided by use statistical tools like Analysis of Variance (ANOVA) [15]. The model equation for a full factorial design with three factors is:

Where: Response variable (dependent variable)

  - Overall mean
  - Main effects of factors A, B, and C
  - Two-factor interactions
  - Three-factor interaction
  - Random error term
- Visualize the Results: Create interaction plots and main effect plots to visualize the impact of factors and their interactions.

3.3.2. Taguchi Method

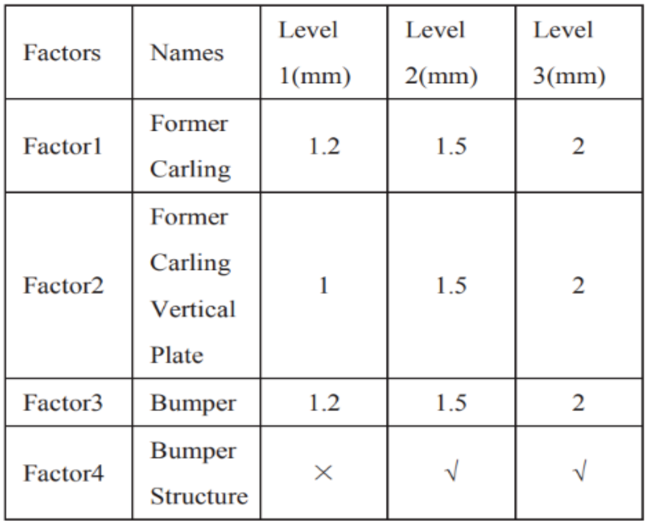
The Taguchi method is a robust design technique focused on improving product and process quality. It emphasizes the use of orthogonal arrays as a method to explore many variables while performing a limited number of experiments. This method uses to analyze effectiveness under varying conditions [16].

3.3.2.1. Steps in the Taguchi Method

- Define the Objective: Clearly state the goal of the experiment, such as improving quality or optimizing performance metrics.

- Select Factors and Levels: Identify the factors to be studied and define their levels

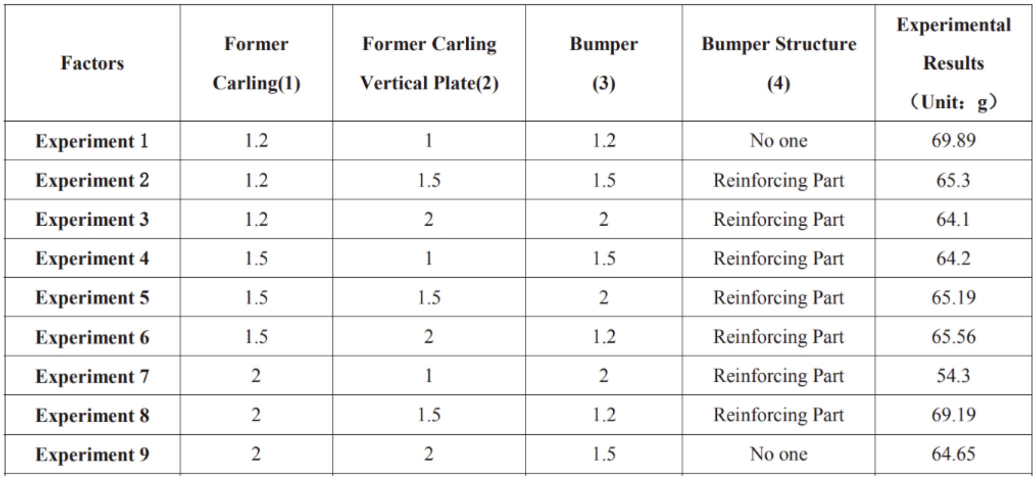
Table 7-example of factors and levels



Factors	Names	Level 1(mm)	Level 2(mm)	Level 3(mm)
Factor1	Former Carling	1.2	1.5	2
Factor2	Former Carling Vertical Plate	1	1.5	2
Factor3	Bumper	1.2	1.5	2
Factor4	Bumper Structure	×	√	√

- Choose an Orthogonal Array: select a suitable orthogonal array base on number of variables and levels to minimize the number of experiments. (this example L9 orthogonal array has selected)
- Conduct the Experiments: Perform the experiments as per the selected orthogonal array, ensuring consistent conditions.

Table 8- Example of experiment result



Factors	**Former Carling(1)**	**Former Carling Vertical Plate(2)**	**Bumper (3)**	**Bumper Structure (4)**	**Experimental Results （Unit：g）**
Experiment 1	1.2	1	1.2	No one	69.89
Experiment 2	1.2	1.5	1.5	Reinforcing Part	65.3
Experiment 3	1.2	2	2	Reinforcing Part	64.1
Experiment 4	1.5	1	1.5	Reinforcing Part	64.2
Experiment 5	1.5	1.5	2	Reinforcing Part	65.19
Experiment 6	1.5	2	1.2	Reinforcing Part	65.56
Experiment 7	2	1	2	Reinforcing Part	54.3
Experiment 8	2	1.5	1.2	Reinforcing Part	69.19
Experiment 9	2	2	1.5	No one	64.65

- Calculate Signal-to-Noise Ratios: Evaluate the quality characteristic using S/N ratios based on the objective. The three scenarios of desirable output are, higher-the-better (HB), lower-the-better (LB), and nominal is better (NB). Equations for the first two scenarios are listed below [16].

$$\text{Equation of HB } = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right)$$

$$\text{Equation of LB} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} yi^2\right)$$

- Analyze the Results: Use the S/N ratios and statistical analysis to determine the optimal factor levels and their contributions.

- Validate the Results: Confirm the findings by conducting validation experiments at the optimal settings.

3.3.3. Comparison: Taguchi Method vs Full Factorial Method

Bellow mentions the comparison table of Taguchi method vs full factorial method [17] [18] [19] [20] [21].

Table 9-Comparison: Taguchi Method vs Full Factorial method

	Taguchi Method	**Full Factorial**
Efficiency	High efficiency, fewer experiments	High but resource-intensive
Robustness	Focus on reducing variation	Focus on comprehensive analysis
Interactions	Limited to lower-order interactions	Captures all interactions
Ease of Implementation	Simple with orthogonal arrays	Complex for many factors

3.3.4. Multi -Objective Optimization

The multi-objective parameter optimization is a systematic approach aimed at discovering the ideal balance among multiple objectives within a system or process. Single-objective optimization, which focus on optimizing one specific parameter, but multi-objective optimization engages with several goals simultaneously, such as improvement of performance, quality, and efficiency.

Weighted Sum Method

The weighted sum method converts multiple objectives into a single objective by assigning weights to each objective:

This method is simple but may not capture all Pareto optimal solutions, especially for non-convex fronts. [21]

The weighted sum method combines all the multi-objective functions into one scalar, composite objective function using the weighted sum

$$F(x) = w_1 f_1(x) + w_2 f_2(x) + \cdots + w_M f_M(x).$$

Pareto Frontier Exploration

evolutionary strategies and genetic algorithms (GAs) are used to estimate the Pareto front. These methodologies result in a diverse set of solutions and progressively optimize them through iterative approaches [22].

Taguchi-Based Multi-Objective Optimization

The Taguchi technique can be enhanced for multi-objective optimization via the synthesis of signal-to-noise (S/N) ratios relevant to multiple objectives into a Singal composite S/N ratio. This allows for simultaneous optimization of quality characteristics. [23]

Normalization ensures that both responses are scaled equally, especially if they have different units or ranges. Below mentions the equation of normalized SN ratio for HB.

$$\text{Normalized S/N Ratio} = \frac{\text{S/N Ratio} - \text{Min(S/N Ratio)}}{\text{Max(S/N Ratio)} - \text{Min(S/N Ratio)}}$$

The composite signal-to-noise (S/N) ratio use as a quantitative measure applied in the Taguchi approach for the optimization of multiple objectives. By integrating the S/N ratios of individual objectives into a single composite value, it facilitates the simultaneous optimization of multiple quality characteristics [23].

$$\text{Composite S/N Ratio} = w_1 \cdot \text{Normalized S/N (Strength)} + w_2 \cdot \text{Normalized S/N (Stretchability}$$

3.3.4.1. Comparison of Methods of Multi-Objective Optimization

Bellow mentions the Comparison of different Methods of Multi-Objective Optimization [24] [21] [23].

Table 10 - Comparison of Methods of Multi-Objective Optimization

	Description	**Advantages**	**Limitations**
Weighted Sum	Converts multiple objectives into a single objective using weights.	Simple and intuitive; widely applicable.	May miss non-convex Pareto solutions; requires appropriate weight selection.
Pareto Frontier Exploration	Uses evolutionary algorithms to approximate the Pareto front with diverse solutions.	Captures diverse solutions; suitable for complex problems.	Computationally expensive; requires expertise to implement.
Taguchi-Based Optimization	Extends Taguchi's method by combining signal-to-noise ratios of multiple objectives.	Efficient for experimental setups; balances multiple objectives.	Limited to predefined orthogonal arrays; may oversimplify complex problems.

3.4. Method of Developing the Process Model (Objective 2 &3)

This study will focus on exploring the adhesive bonding process of the fabric with the polyurethane-based reactive hot melt adhesives commonly referred to as PURs. The process model also shows how bonding strength and stretchability, the outputs of the evaluation process, may be influenced by certain factors namely adhesion promoter treatment and film thickness. Some of these factors were obtained from the literature review and benchmarking on the best organizations. This process model may be used to map all the input parameters to the possible performance characteristics of the bonded fabric assemblies in an orderly manner. With the increasing influence of such factors determined, the balance of the adhesive bonding process will be established and the right parameters to enhance adhesive bonding without diminishing the stretchability property will be developed.

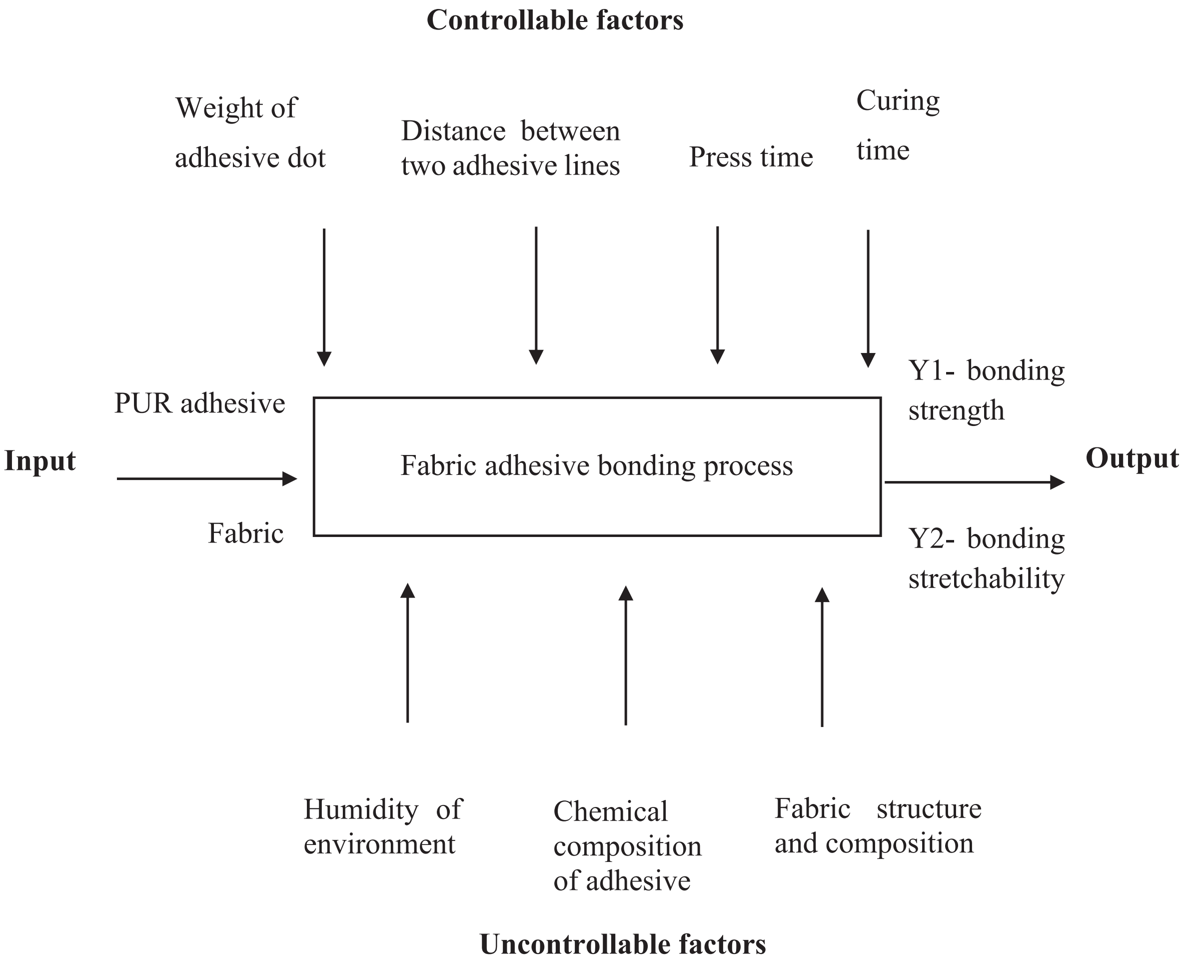


Figure 6- process model

3.4.1. Input parameters

Inputs:

Fabric: The substrate material for bonding.

PUR Adhesive: The bonding agent applied to the fabric.

3.4.1.1. PUR adhesive

PURs are thermosetting adhesives known for their excellent bonding strength, flexibility, and durability. They contain of an isocyanate-terminated polyurethane prepolymer, which reacts with moisture in the environment to cure and form strong chemical bonds.

Generic name – Reactive polyurethane hot melt adhesive

Brand name – NOVATEX - PURTex

Figure 7 - PUR adhesive

3.4.1.2. Fabric material

The fabric is manufacturer using knit-weft double interlock structure. this fabric consists of 80% polyester and 20% elastane, which is well-suited for applications that require stretch and recovery. grams per square meter (GSM) of fabric is 245. The fabric has been subjected to a piece-dyed single-dyed technique, which secures homogenous coloration and an intense visual appeal. Additionally, a chemical moisture management finishing treatment has been applied to enhance wick moisture away from the body.

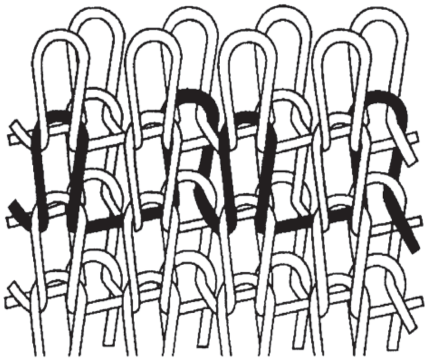


Figure 8 -double interlock weft knitted structure

3.4.2. Uncontrollable Factors

Uncontrollable Factors:

1. **Chemical Composition of Adhesive Polymer**: Determines the intrinsic properties of the adhesive.
2. **Humidity of Environment During Curing**: Influences the curing rate and final properties of the adhesive.
3. **Temperature of Environment**: Affects the flow and reactivity of the adhesive during application and curing.

Several uncontrollable factors can influence the adhesive bonding process, affecting the consistency and reliability of experimental results. One such factor is the chemical composition of the adhesive polymer, which determines the intrinsic properties of the adhesive, such as bonding strength, flexibility, and durability. Since the formulation is predefined by the manufacturer, it cannot be altered during the study. Another critical factor is the humidity of the environment during curing, as variations in humidity levels can impact the curing rate and the final properties of the adhesive. High humidity may lead to slower curing and potential weakening of the bond, while low humidity may accelerate drying but affect adhesion quality. Similarly, the temperature of the environment plays a crucial role in the bonding process, influencing the viscosity, flow, and reactivity of the adhesive. Fluctuations in temperature may lead to inconsistencies in the adhesion performance, making it a significant yet uncontrollable variable. While these factors cannot be directly controlled, their effects can be minimized by conducting experiments in a controlled environment as much as possible and recording environmental conditions to analyze their potential impact on the results.

3.4.3. Controllable Factors

The bonding strength and stretchability of fabric adhesive bonding are influenced by several controllable factors. The weight of the adhesive dot determines the amount of adhesive applied per unit area, directly affecting adhesion quality. The distance between glue dot lines influences the distribution of adhesive, impacting both strength and flexibility. Press time of the machine for adhesive penetration ensures proper bonding by allowing the adhesive to spread and adhere effectively. Lastly, the dual time for curing plays a crucial role in allowing the adhesive to fully develop its bonding properties. Proper control of these factors is essential for optimizing adhesive performance.

Controllable Factors:

1. Weight of adhesive Dot
2. Distance Between Glue Dot
3. Press Time of the Machine for adhesive Penetration
4. Dual Time for Curing

3.3.3.1. Weight of Adhesive dot

The weight of the adhesive dot refers to the precise amount of adhesive applied per unit number of dots during the bonding process. This variable significantly influences the consistency, extent, and comprehensive efficacy of the adhesive joints. A higher weight generally enhances bonding strength by increasing the adhesive contact area but may compromise stretchability if excessive adhesive stiffens the bond. Conversely, insufficient weight may lead to weak bonds with inadequate coverage.

Achieving an optimal glue dot weight ensures a balance between bonding strength and flexibility, critical for applications requiring both durability and elasticity.

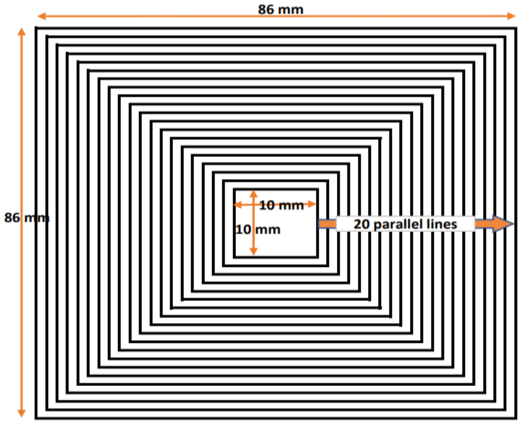


Figure 9: Design for measuring adhesive weight

In this study, an 86mm x 86mm above design is used to measure adhesive dot weight. It consists of a constant number of adhesive dots, is applied to an A5-sized paper. The glue design's weight is determined by first measuring the weight of the A5 paper without adhesive and then re-measuring after applying the adhesive dots. The difference represents the weight of the adhesive in the design.

$$weight\ of\ the\ adhesive = \mathrm{W1} - \mathrm{W2}$$

Where W1: Weight of the paper with adhesive

W2: Initial weight of the paper

Below figure11 shows the actual image of the adhesive dot design for measuring dot weight.

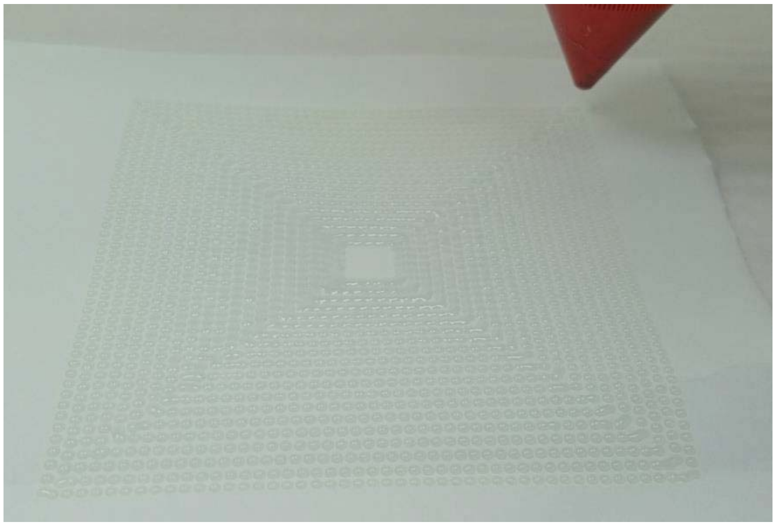


Figure 10- Actual image of adhesive dots for measuring dot weight

3.3.3.2. Distance Between Glue Dot Lines

The distance between adhesive lines determines the coverage. For this study, the design includes 55 adhesive rows within a 15cm length. During testing, a 15cm overlap bond area is used to assess peel strength, following ASTM D1876 standards. These spacing impacts stress distribution and overall bond performance. In practical applications, the X-direction distance between lines can be adjusted as needed. However, the fabric seam width is typically fixed 4 adhesive rows at 1cm, as per industry practice.

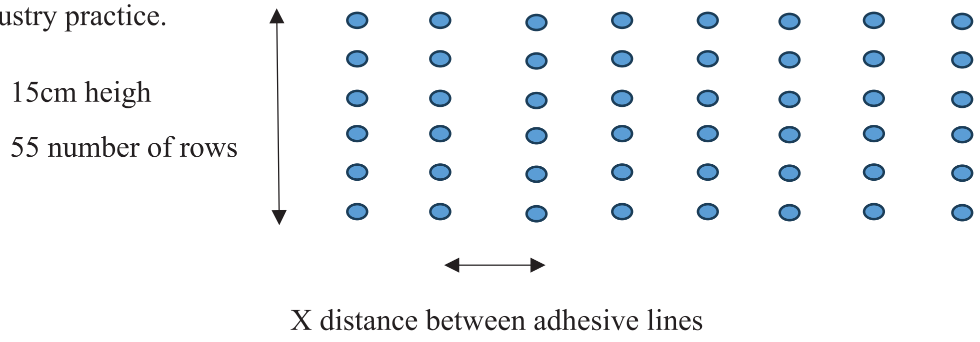


Figure 11- Diagram of glue dots

Bellow figures show the three different spacings between glue dot lines are considered in the X-direction respectively 1mm, 1.8mm, and 2.6mm.

Figure 12- 1.0mm between two glue dot lines

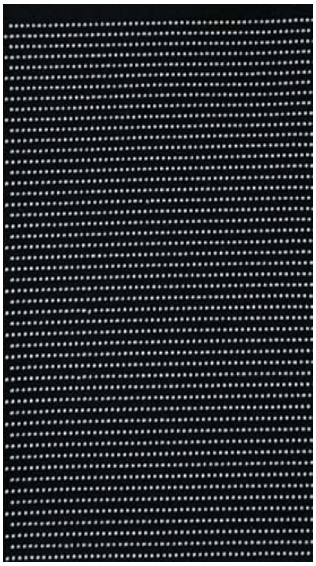


Figure 14- 1.8 mm between two glue dot lines

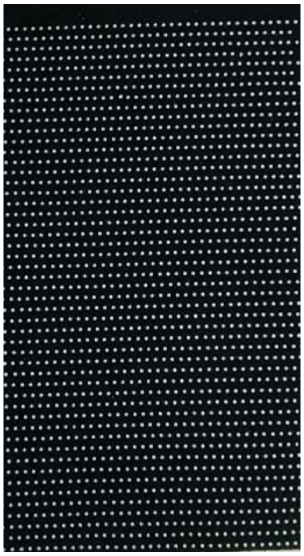


Figure 13 – 2.6mm between two glue dot lines

3.3.3.3. Press time

Press time refers to the duration for which pressure and heat are applied to the adhesive and fabric. This process ensures that the adhesive spreads evenly across the fabric surface and penetrates into its fibers for a strong bond. A pneumatic heat press machine is used for this purpose, equipped with a 25cm x 25cm bed and operating at a constant air pressure of 4 bar. The temperature is set at 70°C, as recommended by the adhesive supplier, to optimize adhesive flow and penetration.

Figure 15-pneumatic heat press machine

The temperature is controlled using an integrated digital thermostat to maintain consistent heat levels throughout the pressing operation. Periodic calibration of the thermostat ensures accurate temperature delivery. A thermal sensor is used to monitor the surface temperature of the press bed to confirm uniform heat distribution across the 25cm x 25cm area.

The press time is controlled using a built-in timer on the pneumatic heat press machine. The time is recorded in seconds, and standard press times are defined for experimental consistency (e.g., 5, 15, 25 seconds). Multiple trials are conducted to determine the optimal press time for maximum bonding performance.

Figure 16 - Control panel of heat press machine

3.3.3.4. Dual Time for Curing

Curing is the chemical process where the adhesive reacts with environmental moisture to form strong cross-links, transforming the adhesive into a solid thermoset material. The curing time provides sufficient duration for these reactions to complete, thereby stabilizing the bond. The application of suitable curing duration is essential for securing the desired bonding strength, stretchability and durability [6] [3].

Trials are conducted at different curing durations (e.g., 4, 14, 24 hours) to evaluate their impact on bond performance. As a norm in the industry, a curing time of **14 hours** is widely used in industry.

Figure 17 - Racks for panel curing

3.4.4. Output Parameters

The two key output parameters in fabric adhesive bonding are bonding peel strength and stretchability. Bonding peel strength measures the force required to separate bonded fabric layers, indicating the adhesive's effectiveness in creating a strong bond. Stretchability, on the other hand, refers to the fabric's ability to elongate without compromising adhesion, which is crucial for applications requiring flexibility. Optimizing these parameters ensures a balance between durability and elasticity in adhesive bonding performance

3.4.4.1. Bonding Peel Strength

The bonding peel strength is measured using the ASTM D1876 standard, commonly known as the "T-Peel Test." This method is specifically designed to evaluate the peel resistance of bonded materials, making it ideal for assessing adhesive bonds in fabric substrates.

The T-Peel Test determines the average force required to separate two bonded materials over a defined length. This test provides insights into the adhesion strength and uniformity of the adhesive bond.

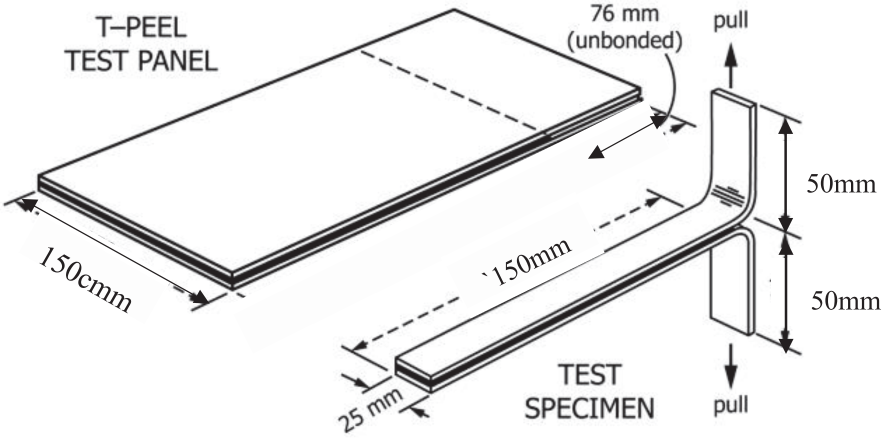


Figure 18 - test specimen

Setup

- This Test is carried out using a universal testing machine (figure 19) that is integrated with a load cell to measure tensile forces.
- The specimen is steadily fixed at both ends, while the unbonded part are securely grasped within the machine's grips.

Figure 19- universal testing machine

Peeling

- The machine applies a constant rate of separation (typically 305mm/min) to pull the bonded fabric strips apart.
- The peeling force is applied perpendicular to the bonded area to ensure accurate measurement.

Data Collection:

- The force required to peel the bonded materials is continuously recorded over the test length.
- The average peel strength is calculated in units of force per width (N/mm).
- The test is repeated for multiple samples to ensure statistical reliability.

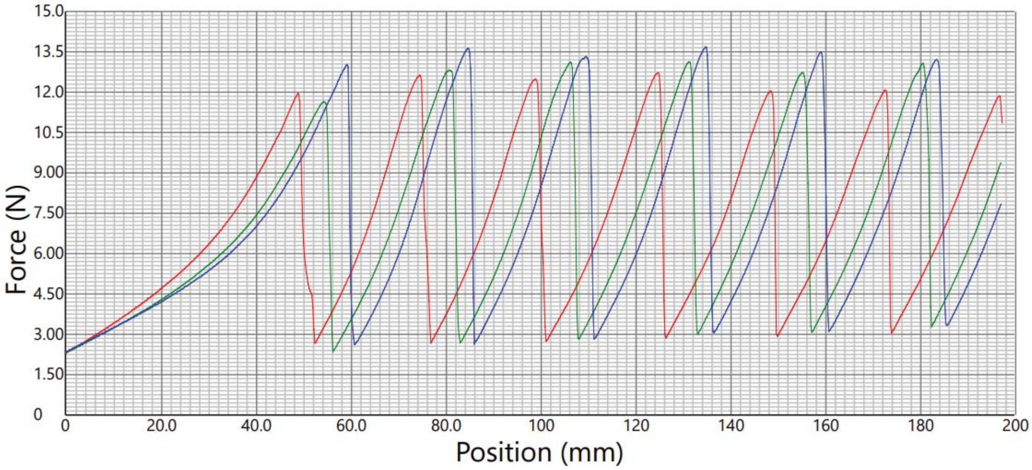


Figure 20 - Graph of peel strength

3.4.4.2. Bonding Stretchability

The ASTM D2594 test method focuses on evaluating the stretch properties of knitted fabrics with low power stretch characteristics. Below is a detailed explanation of its core elements based on the testing standard [25].

suitable for supporting the hanger assembly illustrated in Fig. 25 and tension forces applied during testing

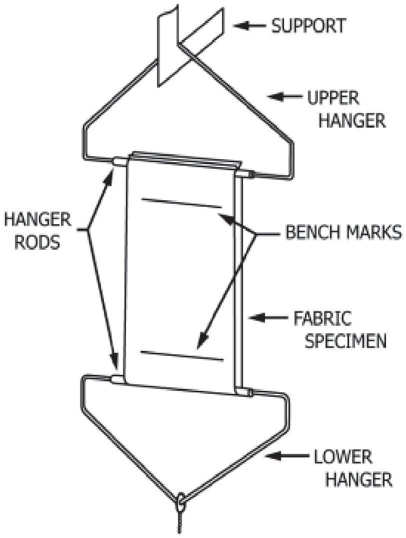


Figure 21-Hanger assembly

Mark benchmark as shown in figure 24 on the fabric specimen. length between two marks is 125 mm (5 inches).

Weights attached to the bottom hanger of the hanger assembly, capable of providing total tensions 4.54 kg (10 lbf) to the specimen,

Figure 22- Actual image of hanger assembly

The fabric stretch is calculated from the length difference between the benchmarks prior to application of the tension and under while under the tension.

$$Fabric\ strechability = \left(\frac{Lf - Li}{Li}\right) X\ 100$$

Where: Lf - length difference between the benchmarks while under the tension

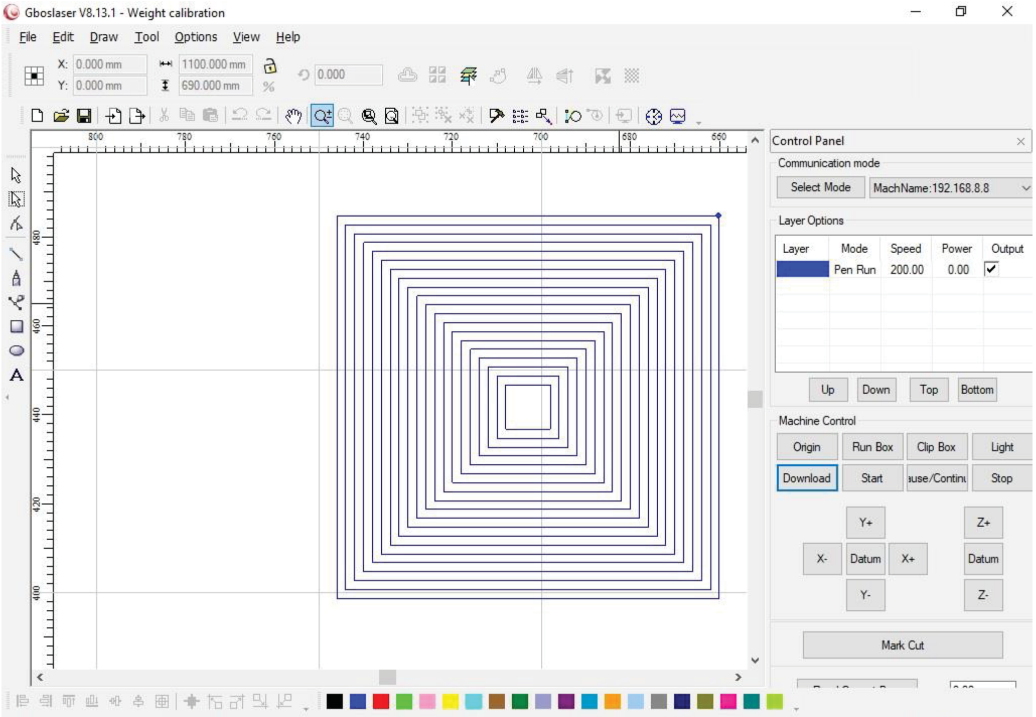
Li – Initial length difference between the benchmarks.

3.5. Apparatus Used for This Research (Objective 2)

The adhesive application machine is widely used in industrial applications involving PUR bonding. This machine is specifically formulated to achieve precision, consistency, and efficiency in the application of adhesives, which makes it exceptionally appropriate for bonding techniques.

Figure 23 - Adhesive application machine

The GBOS adhesive application machine incorporates a CAD system that allows accurate control over adhesive patterns, application sequences, and operational speed. This system facilitates users in creating sophisticated adhesive arrangements, which may include continuous lines, dots to address specific bonding needs.



Layer	Mode	Speed	Power	Output
🟦	Pen Run	200.00	0.00	☑

Figure 24 - CAD software

Once the design and parameters are finalized, the pattern is downloaded directly to the machine's control panel, ensuring seamless execution during production.

Figure 25- Machine control panel

The GBOS adhesive application machine features a versatile control panel that allows operators to adjust key parameters critical for adhesive application. These include:

1. **Open Height**: Controls the nozzle's opening time during glue application, ensuring the precise amount of adhesive is dispensed.
2. **Working Modes**: Operators can switch between modes like *pulse* or *continuous*, with pulse mode commonly used in production for its accuracy and efficiency.
3. **Nozzle Temperature**: Adjustable to match the glue type and its viscosity, typically set between 180°C to 220°C for most production processes.
4. **Barrel Temperature**: Used to heat the adhesive barrel to melt the glue, ensuring a consistent flow during application.
5. **Nozzle Height**: This setting adjusts the height of the firing pin nozzle during glue application, allowing precise control for varying substrate requirements.

These parameters, adjustable via the machine's control panel, provide exceptional flexibility and precision, enabling the GBOS machine to handle a wide range of adhesive bonding applications effectively.

The process model for fabric adhesive bonding is designed to optimize two critical output responses: bonding strength and stretchability. These outputs are essential for evaluating the performance of the adhesive bond. Controllable Factors and Levels

The experimental design focuses on controllable factors that directly influence the adhesive bonding strength and stretchability. Each factor has three levels representing a range of values determined through trials and industry practices.

3.6. Taguchi Design of Experiments (Objective 2)

The Taguchi method is selected for this research due to its efficiency in designing experiments with multiple factors and levels while minimizing the number of experimental runs required. Taguchi’s orthogonal arrays allow for a significant reduction in the number of experiments needed compared to a full factorial design, saving time and resources.

The Taguchi method provides a framework for evaluating the influence of uncontrollable factors, ensuring that the identified optimal conditions are robust under varying environmental conditions.

3.6.1. Experimental Factors and Levels

In this study, experimental factors and their levels are carefully selected to optimize adhesive bonding performance. The key controllable factors include the weight of adhesive dots, distance between glue dot lines, press time for adhesive penetration, and dual curing time. Each factor is tested at different levels to evaluate its impact on the bonding peel strength and stretchability of the fabric.

3.6.1.1. Levels of Adhesive Dot Weight

Levels: 1.1g, 1.26g, 1.42g

- Several trials were conducted to identify the minimum and maximum adhesive weights that ensure quality bonding.
- At lower adhesive weights (1.1g), bonding strength was found to be insufficient due to inadequate adhesive coverage.
- At higher adhesive weights (e.g., 1.42g), larger uneven adhesive dots, as shown in the accompanying image, were observed. These larger dots lead to poor surface uniformity, which is not quality approved.

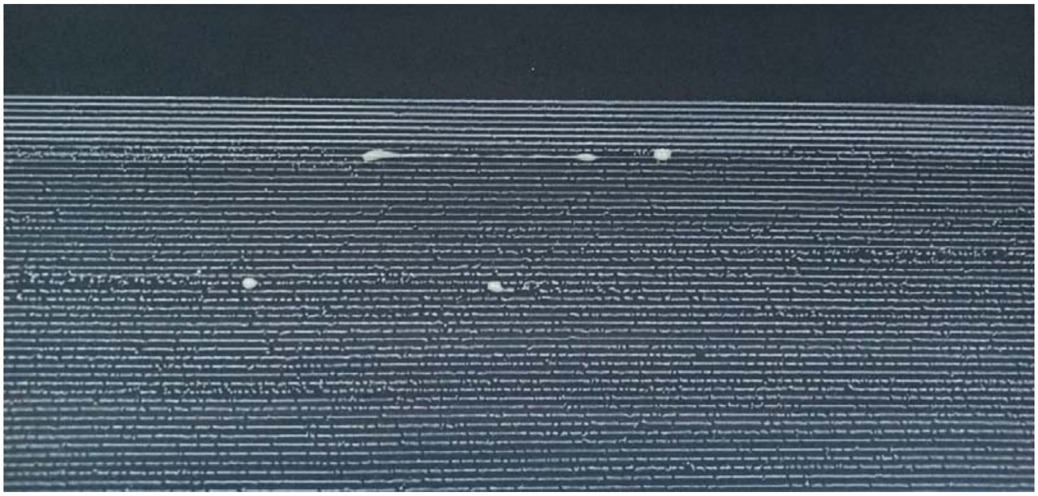


Figure 26- larger uneven adhesive dots

- The selected range ensures a balance between optimal coverage and uniform dot application.

3.6.1.2. Levels of Distance Between Glue Dot Lines

Levels: 1mm, 1.8mm, 2.6mm

- The industry standard distance is 1.8mm, providing adequate adhesive distribution without overusing material.

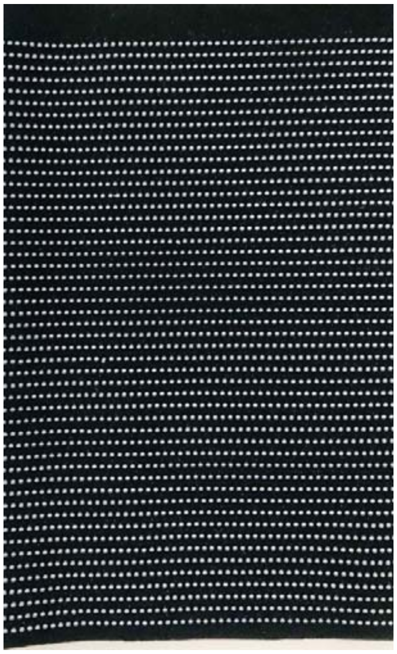


Figure 27 - 1.8mm industry standard

- During trials identified that 1mm distance between glue dot lines give the minimum level for that.
- The chosen levels provide a practical range for optimizing adhesive distribution and bond quality.

3.6.1.3. Levels of Press Time

Levels: 5 seconds, 10 seconds, 15 seconds

- Press time affects adhesive penetration into the fabric structure, influencing bonding strength and uniformity.

- Generally, industry uses 15 seconds press times for this kind of application. It provides sufficient adhesive penetration
- Trials indicated that the shortest press time is 5 seconds for adhesive penetration.
- The selected range ensures optimal adhesive spread and penetration without compromising quality.

3.6.1.4. Levels of Dual Time for Curing

Levels: 4 hours, 14 hours, 24 hours

- Curing time is critical for achieving full cross-linking of the adhesive, which affects bonding strength and elasticity.
- Industry practice typically uses a curing time of 14 hours, ensuring consistent performance.
- The selected levels balance curing efficiency and adhesive performance.

3.6.1.5. Summary Of Factors and Levels

The following table summarizes the factors and their respective levels:

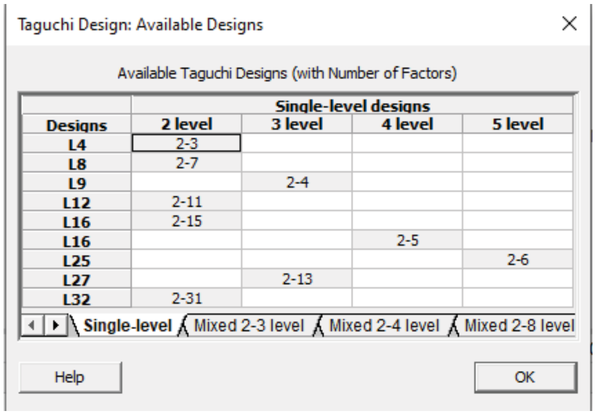
Table 11- Summary of factors and levels

Factor	Level 1	Level 2	Level 3
Weight of glue adhesive (86mm x 86mm) (g)	1.1	1.26	1.42
Distant between two Adhesive dot lines (mm)	1	1.8	2.6
Press time of the machine (sec)	5	15	25
Curing time (Hours)	4	14	24

The identified factors and levels were chosen based on their impact on the quality of the adhesive bond, as demonstrated through preliminary trials and industry practices. By systematically varying these factors, the experimental design aims to identify optimal conditions for achieving high bonding strength and stretchability.

3.6.2. Orthogonal Array

This experiment involves four factors, each at three levels. For a design with 4 factors and 3 levels, the available orthogonal arrays include L9 and L27. The L27 array was selected for this experiment.



Available Taguchi Designs (with Number of Factors)

	Single-level designs			
Designs	**2 level**	**3 level**	**4 level**	**5 level**
L4	2-3			
L8	2-7			
L9		2-4		
L12	2-11			
L16	2-15			
L16			2-5	
L25				2-6
L27		2-13		
L32	2-31			

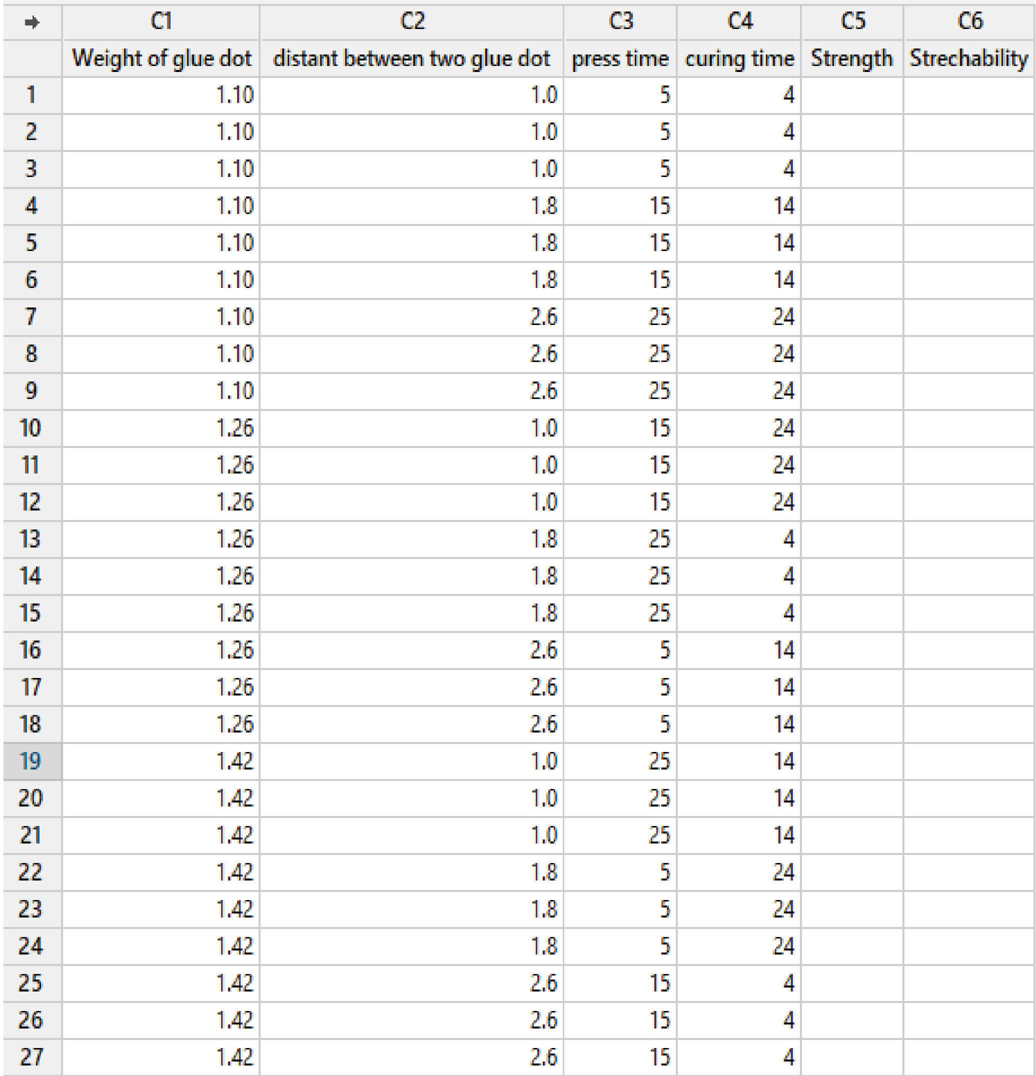
Figure 28- Available design for Taguchi method

The increased number of runs in the L27 array provides higher precision and reliability in estimating the main effects and interactions. This is particularly important in ensuring that the optimal conditions are accurately identified.

While the L9 orthogonal array requires only 9 experimental runs, it does not provide sufficient resolution to study interactions between factors. The L27 array, on the other hand, accommodates interaction effects, enabling a deeper understanding of how factors such as glue dot weight and curing time interact to influence bonding strength and stretchability.

The L27 orthogonal array requires 27 experimental runs, with each run corresponding to a unique combination of factor levels. The table below illustrates the structure of the array for the 4 factors in this experiment. This study was conducted using Minitab software, which simplifies the process of constructing and analyzing.

Table 12- Combinations of experimental runs



➡	C1	C2	C3	C4	C5	C6
	Weight of glue dot	distant between two glue dot	press time	curing time	Strength	Strechability
1	1.10	1.0	5	4		
2	1.10	1.0	5	4		
3	1.10	1.0	5	4		
4	1.10	1.8	15	14		
5	1.10	1.8	15	14		
6	1.10	1.8	15	14		
7	1.10	2.6	25	24		
8	1.10	2.6	25	24		
9	1.10	2.6	25	24		
10	1.26	1.0	15	24		
11	1.26	1.0	15	24		
12	1.26	1.0	15	24		
13	1.26	1.8	25	4		
14	1.26	1.8	25	4		
15	1.26	1.8	25	4		
16	1.26	2.6	5	14		
17	1.26	2.6	5	14		
18	1.26	2.6	5	14		
19	1.42	1.0	25	14		
20	1.42	1.0	25	14		
21	1.42	1.0	25	14		
22	1.42	1.8	5	24		
23	1.42	1.8	5	24		
24	1.42	1.8	5	24		
25	1.42	2.6	15	4		
26	1.42	2.6	15	4		
27	1.42	2.6	15	4		

3.6.3. Experimental Procedure

Bellow describes the step-by-step procedure for conducting the adhesive bonding experiment based on the L27 orthogonal array designed using the Taguchi method.

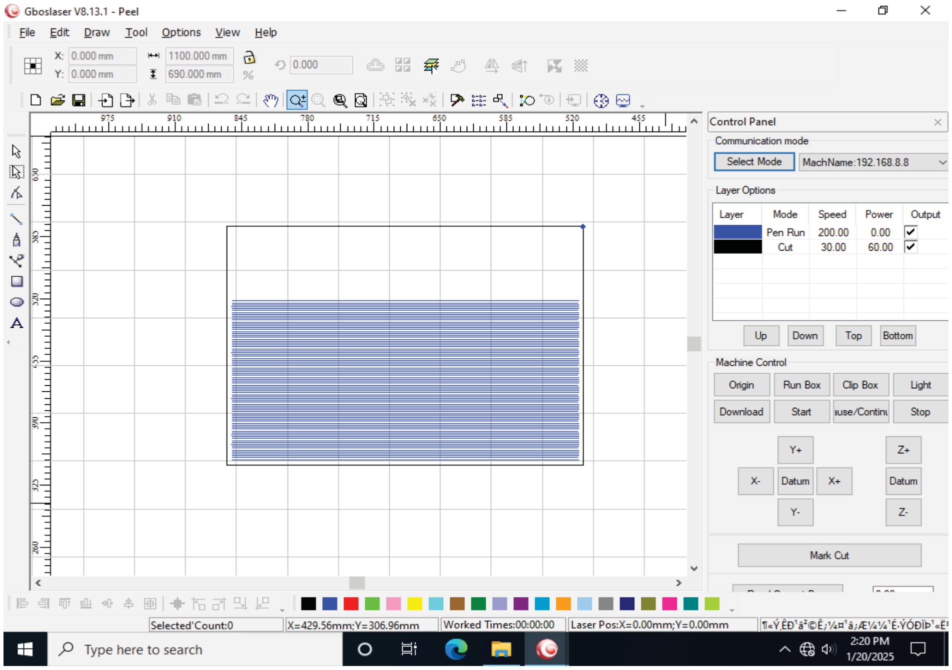
Step 1 - Set the Machine Parameters

Adjust the adhesive weight and distance between glue dot lines as per the specific run in the L27 orthogonal array. It is needed ensure the machine is calibrated to deliver the specified adhesive dot weight and spacing:

Adhesive Weight Levels: 1.1g, 1.26g, 1.42g

Adhesive Dot Line Spacing Levels: 1.0mm, 1.8mm, 2.6mm

Bellow figure shows the software which used to design the adhesive line. Dot Line Spacing Levels is needed to change as per trial data



X: 0.000 mm
Y: 0.000 mm
1100.000 mm
690.000 mm
0.000

MachName:192.168.8.8

Layer	Mode	Speed	Power	Output
🟦	Pen Run	200.00	0.00	☑
■	Cut	30.00	60.00	☑

Selected'Count:0
X=429.56mm;Y=306.96mm
Worked Times:00:00:00
Laser Pos:X=0.00mm;Y=0.00mm

Figure 29 - Software for design adhesive lines

Step 2: Prepare the Fabric Panel and Apply Adhesive

- Place the fabric substrate on the machine’s flatbed to ensure even application of the adhesive.
- Ensure the substrate is lay in correct position and free of wrinkles to avoid uneven bonding.
- Operate the machine to dispense the adhesive as per the specified parameters in the L27 array.

Figure 30- Adhesive application

Step 3: Paste the Second Panel

- Carefully align and place the second fabric panel on top of the adhesive-coated first panel.
- Press gently to ensure the two panels are in contact without displacing the adhesive.

Figure 31- Paste the Second Panel

Step 4: Press the Panels

- Transfer the bonded panel assembly to the pneumatic heat press machine.
- Set the machine to the designated press time and temperature:
    - Press Time Levels: 5s, 10s, 15s
    - Press Temperature: 70°C (as recommended by the adhesive supplier)
- Apply a pressure of 4 bar to ensure proper penetration of the adhesive into the fabric layers.

Figure 32 -Pneumatic heat press machine

Step 5: Cure the Fabric Panels

- Allow the bonded panels to cure under environmental conditions:
    - Curing Time Levels: 4 hours, 14 hours, 24 hours
- Label and store each sample in a clean, dust-free environment to prevent contamination.

Step 6: Repeat for All Runs

- Repeat steps 1 through 5 for each of the 27 runs specified in the L27 orthogonal array.
- Record all machine settings, adhesive application observations, and any deviations from the expected process for each run.

4. RESULTS AND DISCUSSION

The following data table presents the results of the adhesive bonding trials conducted using the L27 orthogonal array. Each trial corresponds to a unique combination of process parameters, including adhesive weight(g), distance between glue dot lines(mm), press time(sec), and curing time(H). The outputs measured were bonding strength (in N/mm) and stretchability (in percentage).

Table 13 - Results of the adhesive bonding trials

No	Weight of adhesive dot	Distance between two dot lines	Press time	Curing time	Strength	Stretchability
1	1.1	1	5	4	0.3	18%
2	1.1	1	5	4	0.27	17%
3	1.1	1	5	4	0.23	18%
4	1.1	1.8	15	14	0.65	42%
5	1.1	1.8	15	14	0.56	39%
6	1.1	1.8	15	14	0.62	42%
7	1.1	2.6	25	24	0.51	54%
8	1.1	2.6	25	24	0.55	54%
9	1.1	2.6	25	24	0.52	51%
10	1.26	1	15	24	1.16	3%
11	1.26	1	15	24	1.09	2%
12	1.26	1	15	24	1.12	6%
13	1.26	1.8	25	4	0.34	40%
14	1.26	1.8	25	4	0.33	34%
15	1.26	1.8	25	4	0.33	38%
16	1.26	2.6	5	14	0.42	60%
17	1.26	2.6	5	14	0.47	62%
18	1.26	2.6	5	14	0.38	60%
19	1.42	1	25	14	0.77	2%
20	1.42	1	25	14	0.82	2%
21	1.42	1	25	14	0.81	2%
22	1.42	1.8	5	24	0.58	56%
23	1.42	1.8	5	24	0.69	50%
24	1.42	1.8	5	24	0.71	53%
25	1.42	2.6	15	4	0.31	46%
26	1.42	2.6	15	4	0.3	46%
27	1.42	2.6	15	4	0.3	43%

4.1. Signal-to-Noise Ratio Analysis (Objective 2)

A detailed analysis of the S/N ratios for bonding strength and stretchability was conducted using the Taguchi method. The S/N ratios provide a robust measure of performance, capturing the variability in outputs under different experimental conditions. The response table created from Minitab software highlights the impact of each factor on the output responses. This analysis allows for identifying the most influential factors and their optimal levels to enhance bonding strength and stretchability.

4.1.1. S/N Ratio for Bonding Strength

Figure 35 shows the Main effect plot. The "higher-the-better" condition was applied for analyzing bonding strength, as this output need to be maximized for optimal adhesive performance.

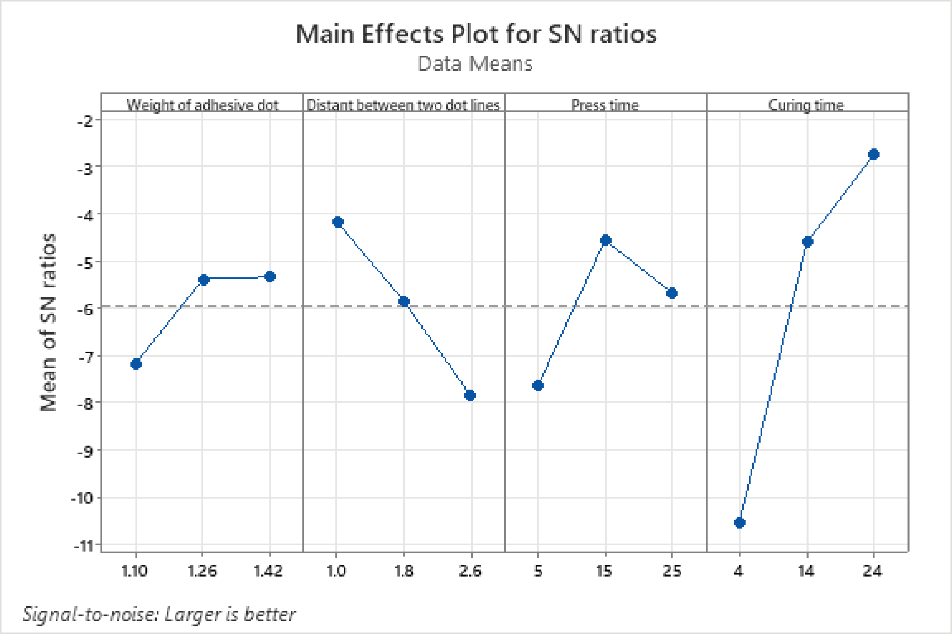


Figure 33 - Main effect plot for SN ratio (Strength)

A detailed examination of the S/N ratio data for bonding strength revealed significant trends across the four factors

For adhesive weight, bonding strength improved significantly as the weight increased up to 1.26g but then declined at 1.42g. The highest S/N ratio was observed at 1.26g, which provided balanced adhesive coverage and uniformity.

For the distance between glue dot lines, closer spacing at 1.0mm produced higher bonding strength due to increased contact points, while wider spacing at 2.6mm reduced strength due to insufficient adhesive distribution. The optimal spacing level was determined to be 1.0mm.

Regarding press time, moderate durations of 15 seconds achieved the best S/N ratio for bonding strength. Shorter times (5 seconds) were insufficient for adhesive penetration, whereas longer times (25 seconds) risked material degradation. The ideal press time of 15 seconds balanced penetration and bond formation effectively.

Curing time analysis revealed that 24 hours of curing provided the highest S/N ratio by achieving optimal cross-linking. Shorter curing times, such as 4,14 hours, resulted in incomplete curing,

Table 14: Response table for SN ratio (Strength)

Level	Weight of adhesive dot	Distant Between two adhesive lines	Press time	Curing time
1	-7.176	-4.195	-7.66	-10.536
2	-5.395	-5.863	-4.573	-4.622
3	-5.35	-7.863	-5.689	-2.764
Delta	1.826	3.668	3.087	7.772
Rank	4	2	3	1

The S/N ratio analysis confirmed that curing time was the most influential factor, followed by glue dot spacing, press time, and adhesive weight. These insights provide a clear understanding of the optimal process parameters for achieving maximum strength.

4.1.2. S/N Ratio for Bonding Stretchability

The analysis of S/N ratios for bonding stretchability, based on the " higher is better" criterion, provides key insights into the performance of various process parameters.

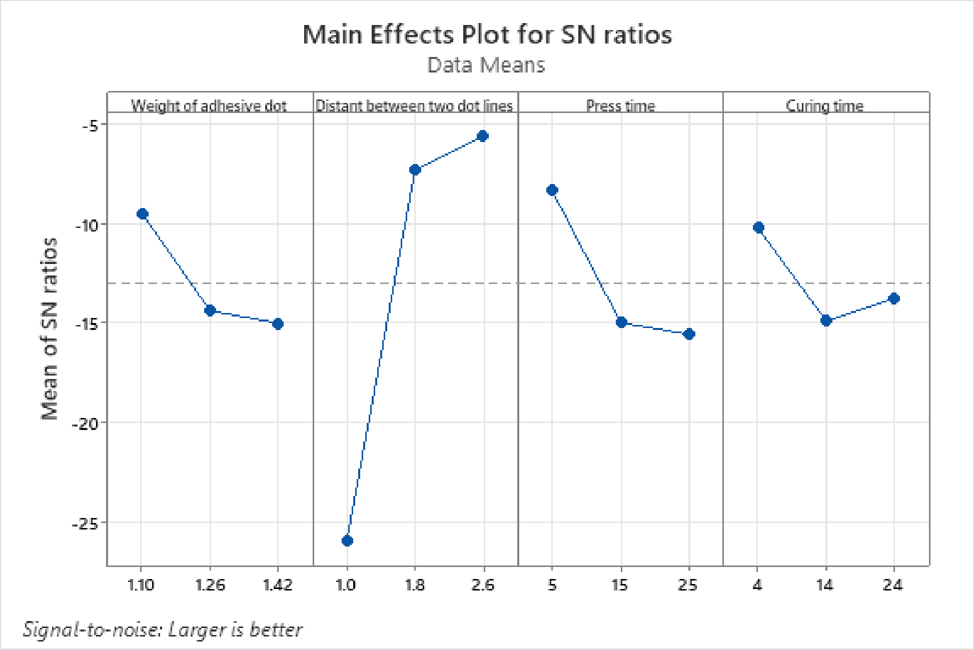


Figure 34 -Main effect plot for SN ratio (Stretchability)

Adhesive weight plays a critical role in determining the flexibility of the bond. The analysis revealed that lower adhesive weights, such as 1.1g, resulted in higher stretchability. This is because lighter adhesive weights reduce the stiffness of the bond, allowing it to elongate more effectively. However, as the adhesive weight increased to 1.26g and 1.42g, the bond became progressively more rigid, reducing its ability to stretch.

Wider spacing, such as 2.6mm, consistently improved the stretchability of the material by reducing bond rigidity. This can be recognized to the fact that increased spacing promotes enhanced flexibility within the adhesive layer. In contrast, a reduction in spacing, represented by 1.0mm, resulted in a decrease in stretchability due to the increased adhesive coverage, which led to a more rigid structural arrangement. It concluded that for maximizing stretchability, adhesive dots should be spaced 2.6mm apart, yielding higher signal-to-noise performance.

The duration of press time considerably influences the penetration of the adhesive. The analysis showed that reduced press durations, such as 5 seconds, improved stretchability by restricting adhesive penetration and preventing the bond from becoming overly rigid. Higher press times, specifically 15,25 seconds, led to greater penetration, consequently increasing bond stiffness while decreasing flexibility. The optimal press time for achieving maximum stretchability was identified as 5 seconds.

Curing duration has an effect on the degree of cross-linking within the adhesive, subsequently influencing the elasticity of the bond. Shorter curing times, such as 4 hours, give the highest stretchability. The optimal curing time for stretchability was identified as 4hours.

Table 15- Response table for SN ratio (Stretchability*)*

Level	Weight of adhesive dot	Distance between two adhesive lines	Press time	Curing time
1	-9.504	-25.946	-8.336	-10.242
2	-14.391	-7.334	-14.993	-14.905
3	-15.012	-5.626	-15.577	-13.76
Delta	5.508	20.32	7.242	4.663
Rank	3	1	2	4

Distance between glue dot lines emerged as the most influential factor affecting stretchability followed by Press time, Weight of the adhesive dot and curing time

4.2. General Linear model – Strength (Objective 2)

4.2.1. Analysis of variance

ANOVA related to bonding strength presents detailed understanding of the influence exerted by each factor on the output response. The analysis includes the four factors: weight of adhesive dot, distance between glue dot lines, press time, and curing time. The ANOVA table summarizes the degrees of freedom (DF), adjusted sums of squares (Adj SS), adjusted mean squares (Adj MS), F-values, and P-values.

Table 16 - ANOVA table(strength)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Weight of adhesive dot	2	0.12029	0.06014	40.69	0
Distance between two dot lines	2	0.45154	0.22577	152.76	0
Press time	2	0.23759	0.1188	80.38	0
Curing time	2	1.02559	0.5128	346.96	0
Error	18	0.0266	0.00148		
Total	26	1.86162			

Weight of Adhesive Dot:

The weight of the adhesive dot significantly impacts bonding strength, with an P-value of 0.000 (<0.05) and F-value of 40.69. This indicates that variations in adhesive weight strongly affect the bonding performance. Optimal adhesive weight ensures balanced coverage and prevents excessive rigidity or weak bonding.

Distance Between Glue Dot Lines:

Distance between glue dot lines significantly impacts bonding strength, with a P-value of 0.00(<0.05) and F-value of 152.76. This highlights its dominant role in determining bonding strength. Closer glue dot lines increase adhesive coverage, improving bonding performance, whereas excessively spaced lines reduce the contact area, weakening the bond.

Press time

Press time significantly impacts bonding strength, with a P-value of 0.00(<0.05) and F-value of 80.38. Adequate press duration ensures the effective penetration of the adhesive into the textile material, while insufficient or excessive press durations result in weak bonding due to incomplete penetration or material degradation.

Curing time

Curing time is the most significant factor affecting bonding strength, with a P-value of 0.00(<0.05), highest adjusted mean square (0.512797) and an F-value of 346.96. Proper curing allows the adhesive to achieve full cross-linking, which is crucial for maximizing bond strength.

Summary of Influential Factors

The ANOVA analysis ranks the factors based on their significance to bonding strength:

1. Curing Time (F-value: 346.96)
2. Distance Between Glue Dot Lines (F-value: 152.76)
3. Press Time (F-value: 80.38)
4. Weight of Adhesive Dot (F-value: 40.69)

Curing time is the most influential factor, emphasizing the importance of optimizing this parameter to achieve the desired bond strength. The distance between glue dot lines and press time are also critical, while the weight of adhesive dot, although significant, has a relatively lower impact.

4.2.2. Residual Plots for Strength

The residual plots for bonding strength were analyzed to validate the assumptions of the ANOVA model. Normality and independence of residuals are discussed in these plots. It ensures the reliability of the statistical analysis.

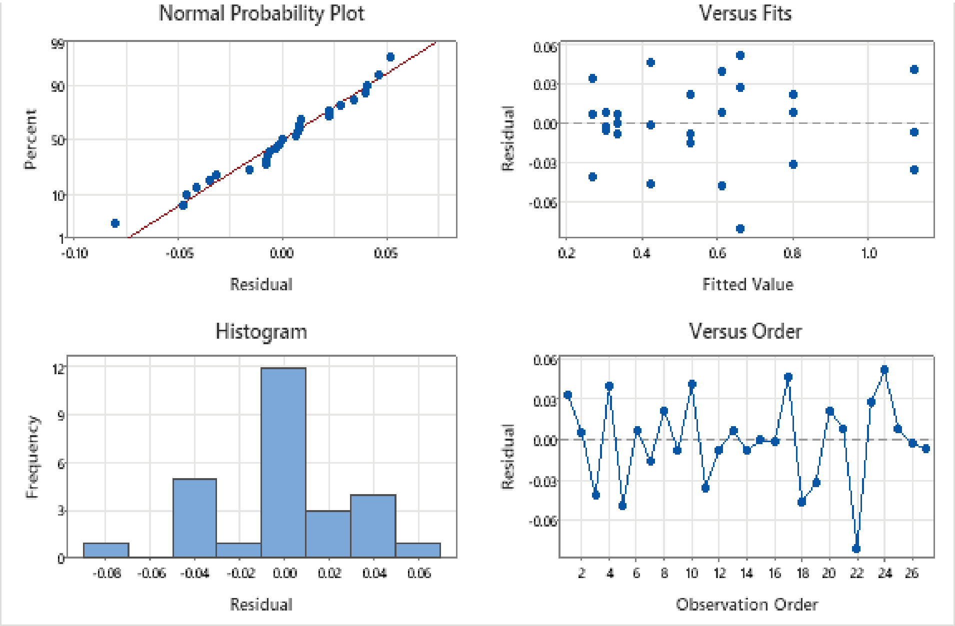


Figure 35 - Residual plots for strength

Normal Probability Plot

The normal probability plot of residuals indicates whether the residuals follow a normal distribution. In this analysis, the residuals aligned closely with the 45-degree reference line, confirming that the assumption of normality is met. Minor deviations observed at the tails are within acceptable limits, ensuring the robustness of the model.

Histogram of Residuals:

The histogram of residuals of figure 34 shows a symmetrical bell-shaped distribution centered around zero. This further supports the normality assumption and indicates that the residuals are not skewed or heavily tailed.

Residuals vs. Fitted Values:

This plot examines the relationship between residuals and predicted values. The residuals are randomly scattered around the zero line, with no clear patterns or trends. This validates that the requirement of consistent variance is fulfilled, illustrating that the spread of residuals does not rely on the predicted values.

Residuals vs. Order:

The residuals vs. order plot assesses the independence of residuals over time. The residuals do not display systematic trends or patterns, confirming that there is no correlation with the order of data collection. This ensures that the residuals are independent.

In summary, an absence of significant variations from the foundational assumptions ensures the accuracy and robustness of the ANOVA analysis.

4.3. General Linear Model – Stretchability (Objective 2)

4.3.1. Analysis of variance

The following ANOVA table related to bonding stretchability highlights the ways in which different factors impact the bond's flexibility.

Table 17- Analysis of variance (Stretchability)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Weight of adhesive dot	2	0.00689	0.00345	10.28	0.001
Distance between two dot lines	2	1.01328	0.50664	1511.18	0
Press time	2	0.10941	0.05471	163.18	0
Curing time	2	0.00477	0.00239	7.12	0.005
Error	18	0.00603	0.00034		
Total	26	1.14039			

Weight of Adhesive Dot

The weight of the adhesive dot significantly impacts to stretchability, as indicated by a P-value of 0.001 (<0.05) and F-value of 10.28. Lower adhesive weights generally result in higher stretchability, as excessive adhesive stiffens the bond, reducing its ability to elongate.

Distance Between Glue Dot Lines

The most significant factor affecting stretchability is the distance between glue dot lines, with an F-value of 1511.18 and a P-value of 0.000(<0.05). Wider spacing, such as 2.6mm, results in greater flexibility by reducing the bond's rigidity. Closer spacing leads to denser adhesive coverage, which can make the bond more rigid and less stretchable.

Press Time

Press time also has a significant impact on stretchability, with an F-value of 163.18 and a P-value of 0.000(<0.05). Shorter press times, such as 5 seconds, result in higher stretchability by preventing excessive adhesive penetration. Longer press times increase stiffness, reducing the bond's flexibility.

Curing Time

Curing time has a moderate influence on stretchability, with an F-value of 7.12 and a P-value of 0.005(<0.05).

Summary of Influential Factors for Stretchability

The ANOVA analysis ranks the factors based on their significance to bonding stretchability:

1. Distance Between Glue Dot Lines (F-value: 1511.18)
2. Press Time (F-value: 163.18)
3. Weight of Adhesive Dot (F-value: 10.28)
4. Curing Time (F-value: 7.12)

Distance between glue dot lines is the most influential factor affecting stretchability. The analysis demonstrates that optimizing this factor is crucial for achieving a balance between bonding strength and flexibility.

4.3.2. Residual Plots for Stretchability

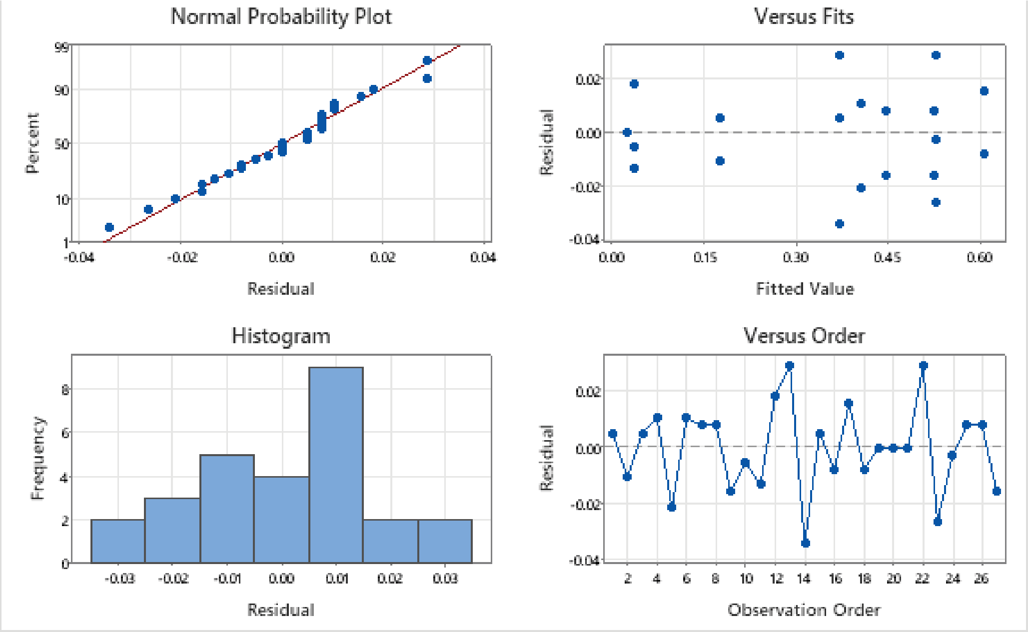


Figure 36- Residual Plots for Stretchability

Normal Probability Plot

The normal probability plot for stretchability shows that the residuals closely follow the 45-degree reference line, indicating that the residuals are normally distributed.

Histogram of Residuals

The histogram of residuals displays a bell-shaped curve centered around zero. This symmetrical distribution supports the normality assumption and indicates that there are no significant outliers or skewness in the residuals.

Residuals vs. Fitted Values

The residuals vs. fitted values plot demonstrates that the residuals are randomly scattered around the zero line. There are no discernible patterns or trends, indicating that the assumption of constant variance is met.

Residuals vs Order

The residuals vs. order plot shows the residuals plotted against the sequence in which the data was collected. The residuals are randomly distributed without any noticeable trends or systematic patterns, confirming that the residuals are independent of the order of data collection.

4.4. Multi-Objective Optimization (Objective 2)

4.4.1. Individual Optimum Values for Strength and Stretchability

The optimum values for each factor were determined separately for bonding strength and stretchability by analyzing the S/N ratios using the "higher-the-better" criterion. However, the optimum values identified for each factor differed between the two responses

Table 18 - Optimum level for strength and stretchability

Factor	**Optimum level for strength**	**Optimum level for Stretchability**
Weight of Adhesive Dot (g)	1.42	1.1
Distance Between Glue Dot Lines(mm)	1.00	2.6
Press Time (Sec)	15	5
Curing Time (h)	24	14

The differing optimum values for strength and stretchability highlight the need for a multi-objective optimization approach. In real-world applications, both bonding strength and stretchability are crucial for ensuring the durability and flexibility of adhesive bonds.

Multi-objective optimization aims to identify a balanced set of process parameters that maximize both bonding strength and stretchability simultaneously. This approach involves the normalization of the SN ratios corresponding to each response, followed by combining them into a composite SN ratio. The composite ratio considers the relative importance of each response

4.4.2. Composite S/N Ratio

The first step in multi-objective optimization is to normalize the S/N ratios for both bonding strength and stretchability. Normalization helps to bring SN ratios of strength and stretchability into the same scale, allowing for a fair comparison.

$$\text{Normalized S/N Ratio} = \frac{\text{S/N Ratio} - \text{Min(S/N Ratio)}}{\text{Max(S/N Ratio)} - \text{Min(S/N Ratio)}}$$

After normalization, the composite S/N ratio is calculated by assigning weightages to each response. Since no specific weightages for strength and stretchability in knitted fabrics were found in the literature, the weights were determined based on the insights provided by industry experts.

4.4.3 Weightages Finalization

The Analytic Hierarchy Process (AHP) was employed to justify the selection of weightages for bonding strength and stretchability in the multi-objective optimization process. AHP is a well-established multi-criteria decision-making (MCDM) technique that quantifies subjective expert judgment through pairwise comparisons, producing objective priority values. In this study, two main performance criteria—bonding strength and stretchability—were evaluated. A panel of industry experts, including product engineers, quality assurance managers, and textile technologists, participated in the evaluation. They were asked to assess the relative importance of bonding strength versus stretchability using Saaty's 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance of one factor over another. The consensus from the pairwise comparison was that bonding strength is moderately more important than stretchability, reflecting its critical role in product durability and failure resistance. The resulting comparison matrix was normalized, and eigenvector values were calculated to determine the relative weights.

Step 1 : Construct the Pairwise Comparison Matrix

Criteria	Bonding Strength (C1)	Stretchability (C2)
Bonding Strength (C1)	1	1.5
Stretchability (C2)	1/1.5	1

Step 2 : Column Totals

Column 1 (C1): 1 + 0.667 = 1.667

Column 2 (C2): 1.5 + 1 = 2.5

Step 3: Normalize the Matrix

Criteria	C1	C2
Bonding Strength (C1)	1 / 1.667 ≈ 0.60	1.5 / 2.5 = 0.60
Stretchability (C2)	0.667 / 1.667 ≈ 0.40	1 / 2.5 = 0.40

This process yielded a weight of **0.6 for bonding strength** and **0.4 for stretchability**, supporting a more practical, performance-based prioritization. This approach ensures that the composite S/N ratio used in optimization aligns with industry needs while remaining methodologically rigorous. The use of AHP thus provides a transparent, justifiable, and replicable basis for weighting selection, avoiding arbitrary equal weighting and reflecting the real-world impact of each criterion.

Table 19- Mini tab composite SN ratio

No	SN ratio - strength	SN ratio-Stretchability	Normalized SN ratio-strength	Normalized SN ratio-Strech	Composite SN ratio
1	-11.646	-15.121	0	0.61792	0.24717
2					
3					
4	-4.3123	-7.8298	0.58015	0.87663	0.69874
5					
6					
7	-5.5705	-5.5605	0.48061	0.95715	0.67123
8					
9					
10	0.99494	-30.183	1	0.08348	0.63339
11					
12					
13	-9.5606	-8.6381	0.16496	0.84795	0.43815
14					
15					
16	-7.6188	-4.3506	0.31857	1	0.59114
17					
18					
19	-1.9346	-32.534	0.76825	0	0.46095
20					
21					
22	-3.7155	-5.5349	0.62736	0.95806	0.75964
23					
24					
25	-10.401	-6.9668	0.09847	0.90725	0.42198
26					
27					

$$\text{Composite S/N Ratio} = w_1 \cdot \text{Normalized S/N (Strength)} + w_2 \cdot \text{Normalized S/N (Stretchability)}$$

These weightages reflect the practical requirements of the textile industry, where maintaining a strong and durable bond is prioritized, but flexibility is still essential for comfort and performance. By using these weightages, the composite S/N ratio was calculated by the below equations for each trial, providing a balanced metric that considers both strength and stretchability.

4.4.3. Optimum Process Parameters Based on Composite S/N Ratio

The composite S/N ratio considers both bonding strength and stretchability, with weightages of 60% for strength and 40% for stretchability.

Table 20 - Response tabel of composite SN ratio

Level	Weight of adhesive dot	Distant Between two adhesive lines	Press time	Curing time
1	-6.239	-7.611	-6.365	-8.934
2	-5.233	-4.223	-4.858	-4.802
3	-5.536	-5.174	-5.786	-3.272
Delta	1.005	3.388	1.507	5.662
Rank	4	2	3	1

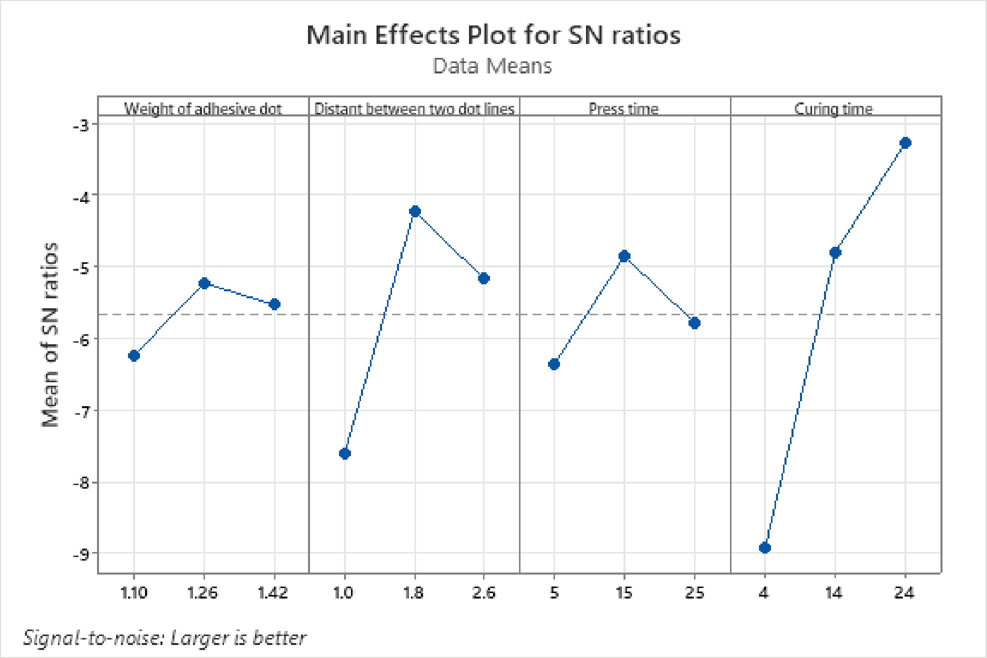


Figure 37 - Main effect plot for Composite SN ratio

Weight of adhesive dot

the second level (1.26g) provided the best composite S/N ratio, balancing strength and stretchability. While the highest adhesive weight (1.42g) maximizes bonding strength, it compromises flexibility. Therefore, 1.26g is the optimum value for achieving a balance.

Distance between glue dot lines

the second level (1.8mm) provided the best composite S/N ratio. This spacing offers a good balance between coverage for strength and flexibility for stretchability.

Press time

The second level (15 seconds) was identified as the optimum press time. It provides enough time for adhesive penetration without making the bond too rigid, achieving a good compromise between strength and flexibility.

Curing time

The third level (24 hours) yielded the best composite S/N ratio. While shorter curing times improve stretchability, longer curing times ensure complete cross-linking, which enhances bonding strength.

Table 21 -Optimum Process Parameters

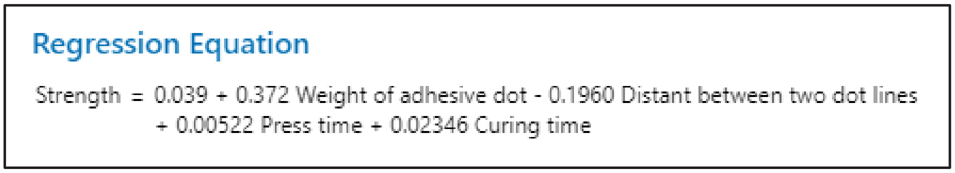
Factor	**Optimum value**
Weight of Adhesive Dot (g)	1.26
Distance Between Glue Dot Lines(mm)	1.80
Press Time (Sec)	15
Curing Time (h)	24

4.5. Prediction of Results for Optimum Parameters (Objective 3)

To validate the performance of the identified optimum process parameters for adhesive bonding, regression equations were used to predict the bonding strength and stretchability outcomes. The regression analysis provides a mathematical model that estimates the expected performance based on the input factors. Below are the detailed regression equations for bonding strength and stretchability, along with the predicted results at the optimum parameter levels.

4.5.1. Prediction for Strength

The regression equation for bonding strength is as follows.

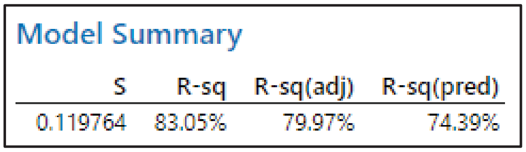


Regression Equation

Strength = 0.039 + 0.372 Weight of adhesive dot - 0.1960 Distant between two dot lines
+ 0.00522 Press time + 0.02346 Curing time

Figure 38- Regression equation (Strength)

The R-squared (R²) value of 83.05% in the linear regression model for adhesive bonding strength indicates that the model explains 83.05% of the variability in bonding strength based on the input variables. This suggests a strong correlation between the selected predictors and the bonding strength, implying that the model is highly effective in capturing the underlying trends.



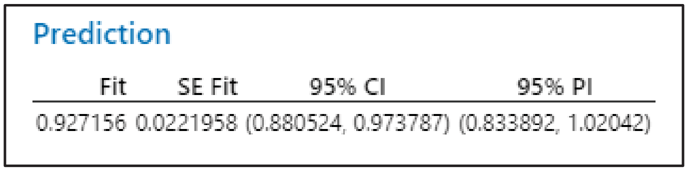
Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.119764	83.05%	79.97%	74.39%

Figure 39 - Model summary

Using the optimum process parameters identified through the composite S/N ratio analysis:

- Adhesive Weight: 1.26g
- Distance Between Glue Dot Lines: 1.8mm
- Press Time: 15 seconds
- Curing Time: 24 hours



Prediction

Fit	SE Fit	95% CI	95% PI
0.927156	0.0221958	(0.880524, 0.973787)	(0.833892, 1.02042)

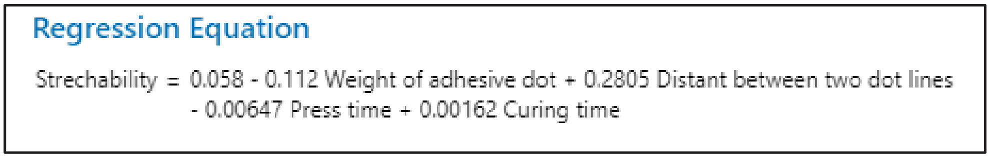
Figure 40 - Mini tab perdition for strength

The predicted bonding strength is 0.927156 N/mm. bonding strength falls within the range of 0.88052 to 0.97378 N/mm at a 95% confidence level.

This prediction confirms that the selected process parameters will achieve a high level of bonding strength, ensuring durability in bonded knitted fabrics.

4.5.2. Prediction for Stretchability

The regression equation for stretchability is as follows.

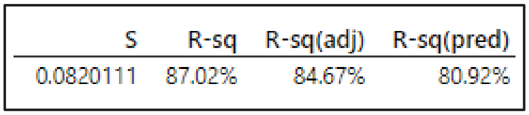


Regression Equation

Strechability = 0.058 - 0.112 Weight of adhesive dot + 0.2805 Distant between two dot lines
- 0.00647 Press time + 0.00162 Curing time

Figure 41- Regression equation (Stretchability)

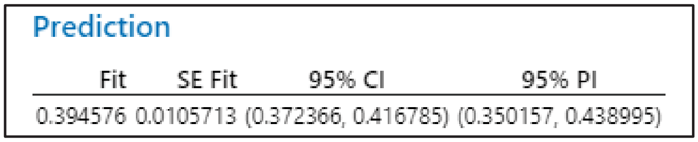
The R-squared (R^2) value of 87.02% in the linear regression model for stretchability suggests that the model effectively explains 87.02% of the variation in stretchability based on the chosen predictors. This high R^2 value indicates a strong relationship between the independent variables and stretchability, making the model highly reliable for analyzing this property.



S	R-sq	R-sq(adj)	R-sq(pred)
0.0820111	87.02%	84.67%	80.92%

Figure 42- Model summary

The predicted stretchability is 0.39457 (39.46%). At a 95% confidence level, the stretchability falls within the range of 0.37236 to 0.41678 (37.24% to 41.68%). These results demonstrate that the selected parameters provide a good balance between bonding strength and flexibility, which are essential for practical applications in knitted fabric bonding.



Prediction

Fit	SE Fit	95% CI	95% PI
0.394576	0.0105713	(0.372366, 0.416785)	(0.350157, 0.438995)

Figure 43- Mini tab perdition for stretchability

Below mentions the Summary of Predicted Optimum Results.

Table 22 - Summary of Predicted Optimum Results

Response	Predicted Value	95% Confidence Interval
Strength (N/mm)	0.927156	0.88052 to 0.97378
Stretchability (%)	39.46	37.24 to 41.68

4.6. Validation of Test Results (Objective 3)

The validation test was executed to confirm the validity of the predicted results after the determination of the optimal parameters through multi-objective optimization. The optimum process parameters used for this validation test were adhesive weight:1.26g, distance between glue dot lines:1.8mm, press time:15 seconds, curing time:24 hours.

This validation test aimed to compare the actual bonding strength and stretchability values obtained through experimental testing with the predicted values from the regression analysis.

The actual test results obtained from the validation experiment were:

- Strength: 0.90 N/mm
- Stretchability: 38.03%

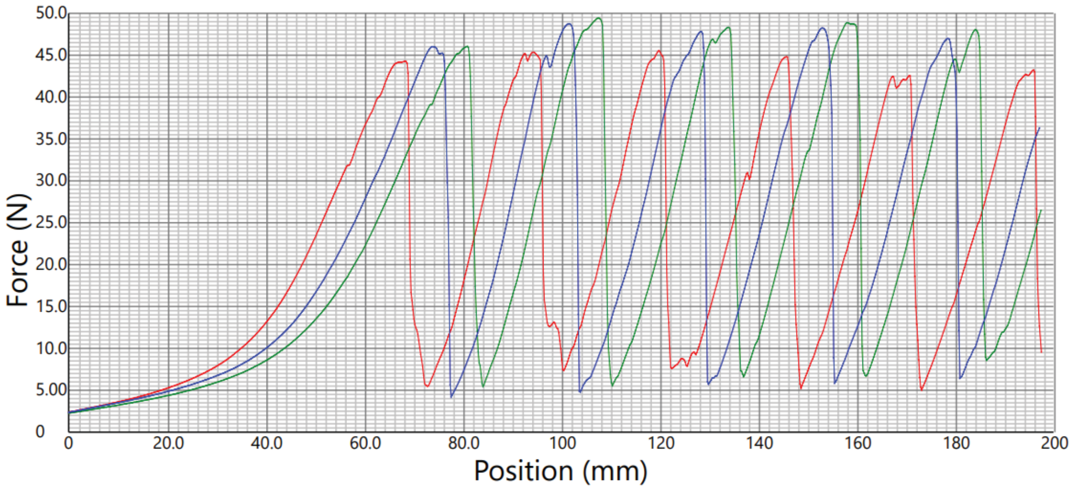


Figure 44 - Graph of peel strength

The validation test results are compared below with the predicted values:

Table 23- Validation test results comparison

Response	**Predicted Value**	**Actual Value**	**Difference (%)**
Strength (N/mm)	0.927	0.90	-2.9%
Stretchability (%)	39.46	38.03	-3.7%

The validation test results closely match the predicted values from the regression equations. The differences detected between the projected and actual values were minimum, pointing to a considerable degree of precision in the optimization technique.

For bonding strength, the actual result of 0.90 N/mm, falls within the 95% confidence interval of 0.88052 to 0.97378N/mm, showing that the process parameters identified through this study reliably achieve strong adhesive bonds.

for stretchability, the actual value of 38.03% is also within the 95% confidence interval of 37.24% to 41.68%. The gap between the predicted and real values is 3.70%, a percentage that lies within a acceptable margin of error for industrial applications.

The findings from the validation test confirm that the optimized process parameters are efficient in achieving the intended balance between bonding strength and stretchability. The actual findings show that the bonded fabric samples comply with the specified performance requirements for both durability and flexibility.

The adhesive bonding strength shown during the validation test confirms that the adhesive joint is capable of withstanding external forces without facing failure, thus making it suitable for practical applications. Simultaneously, the stretchability results indicate that the bond maintains its flexibility and does not compromise the comfort and usability of the fabric.

These results validate the multi-objective optimization framework implemented in this study and highlight its relevance within the area of textile adhesive bonding. By employing these parameters, manufacturers can achieve consistent bonding quality that meets both strength and flexibility standards, thus enhancing the performance of bonded knitted fabrics.

5. CONCLUSION

This study concentrated on the optimization of the adhesive bonding process for knitted fabrics using polyurethane-based reactive hot melt adhesives. The primary objective was to determine the optimal process parameters of bonding strength and stretchability. These two critical properties are necessary for the functionality and comfort of bonded fabrics. The research followed a structured approach, involving a Taguchi-based DoE, ANOVA, regression analysis, and validation testing, to determine that the optimized parameters deliver reliable outcomes in practical applications.

The study began by identifying four key process parameters that significantly affect bonding performance. They are adhesive weight, distance between glue dot lines, press time, and curing time. An L27 orthogonal array was selected to develop experimental designs with factors at three different levels. The outputs (bonding strength and stretchability) were analyzed using S/N ratios to address process variability and enhance performance consistency.

Through the detailed analysis of S/N ratios, it was explained that the optimal conditions for adhesive strength and stretchability were not same. For example, the optimal adhesive weight for achieving maximum bonding strength was 1.42g and also optimal adhesive weight for achieving maximum bonding stretchability was 1.1g. Similarly, the curing time showed different optimal values for the two responses, with longer curing time suitable for bonding strength and a shorter curing time being suitable for stretchability. This shows the requirement for a multi-objective optimization approach.

The multi-objective optimization was conducted by normalizing the S/N ratios for both responses and calculating a composite S/N ratio, assigning 60% weightage to strength and 40% weightage to stretchability. These weightages were determined based on input from industry experts, due to the absence of relevant data in the existing literature. The composite S/N ratio analysis identified the following optimum process parameters:

- Adhesive Weight: 1.26g
- Distance Between Glue Dot Lines: 1.8mm
- Press Time: 15 seconds

- Curing Time: 24 hours

A validation test was performed to verify the accuracy of the optimization process. The actual test results—bonding strength of 0.90 N/mm and stretchability of 38.03% closely matched the predicted values from the regression analysis. This confirms that the optimized parameters provide a reliable balance between durability and flexibility, ensuring the practical applicability of the results in industrial settings.

The analysis further showcased the capability of using regression equations to estimate the performance of adhesive-bonded fabrics in relation to different processing conditions. The predicted outcomes for bonding strength and stretchability fell within the 95% confidence intervals, thereby enhancing the reliability of the regression models.

5.1. Objective achievements

The research successfully fulfilled all four defined objectives, as outlined in the conclusion. First, the study comprehensively analyzed the chemical composition of PUR adhesives and identified the key process parameters influencing both bonding strength and stretchability. Second, through a structured experimental design, the impact of each parameter was evaluated, and the optimal combination was determined to maximize performance. Third, regression-based prediction models were formulated for each input factor, enabling the prediction of adhesive bonding performance with high accuracy. Finally, these models were validated using experimental data, confirming their reliability in estimating real-world outcomes. The successful completion of all objectives demonstrates the robustness of the research methodology and its practical relevance to industrial applications.

Table 24: Objective achievements

No	Objectives	Status
Objective 1	To understand the chemical composition of adhesives and identify process parameters affecting the bond's strength and stretchability.	Completed
Objective 2	To evaluate the impact of process parameters and determine the optimal combination for maximum strength and stretchability	Completed
Objective 3	To formulate prediction models for each input parameter to determine their effects on the adhesive bonding performance.	Completed
Objective 4	To validate the predictive models using experimental data to ensure accuracy and reliability in estimating adhesive bond performance.	Completed

5.2. The Key Findings

The weight of adhesive dots significantly influences the bond's strength, wherein increased adhesive weights enhance strength while simultaneously reducing flexibility. The distance between adhesive dot lines significantly impacts bonding stretchability. Wider spacing improves flexibility, while closer spacing enhances strength. The pressing duration and curing time are critical factors in determining both adhesive bonding strength and stretchability. A moderate press time of 15 seconds, adhesive Weight of 1.26g, Distance Between Glue Dot Lines of 1.8mm and a curing time of 24 hours provided the best balance between these two properties

This research contributes to the current knowledge base of fabric adhesive bonding. It provides a thorough analysis of the process parameters and their resultant effects on the performance of adhesive-bonded fabrics. The combination of the Taguchi method and multi-objective optimization provides an efficient and reliable experimental model. It reduces the requirement for trial-and-error techniques in industry.

The findings obtained from this study exhibit significant applicability across various fields that incorporate bonded textiles, such as sportswear, lingerie, medical textiles, and automotive interiors. By implementing the optimized process parameters, manufacturers can improve both the durability and comfort of bonded fabrics, enhancing product performance and customer satisfaction.

5.3. Limitations of Research

This paper aimed at multi-objective parameter optimization in fabric adhesive bonding using polyurethane-based reactive hot melt adhesives is hereby summarized with several limitations, which could be useful to understand some fundamental findings of the research work as follows.

The research was mainly restricted to PUR adhesives and thus the generalization of the study results may not be purely relevant to other types of adhesives. Further research has to be conducted to investigate more types of adhesives, such as bio-adhesives and epoxy adhesives, to observe if similar optimization ratios can be attained.

This work aimed at using a certain type of knitted fabric with the fabric composition of 80% polyester and 20% Elastane. This limits the generalization of the study results to other fabric materials like natural fibers or different synthetic fiber blend. These decisions could affect bonding performance besides influencing the stretchability of the fabric material known to be of varying compositions.

A major weakness observed in the study is that all activities were undertaken under laboratory settings hence, identifying practical environmental conditions may not be well depicted. Several conditions like humidity, temperature variation and excessive exposure to other light, such as UV light, were not put into practice, and as such, the long–term effectiveness of the adhesive bonds in real-life application may be compromised.

The application of the developed Taguchi method is efficient when used to optimize multiple parameters, but it may not be efficient in capturing interaction effects. There could also be a confounding effect of some variables which could not be noticed outright because of restrictions in the study design.

5.4. Further research opportunities

The following is the list of future research areas in regard to the current multi-objective parameter optimization study of the fabric adhesive bonding using PUR-based adhesives:

As this study was conducted on PUR adhesives, a study can be done on the other types of adhesives, such as the bio-based adhesive or epoxy resin, under similar bonding conditions. This would help compare and contrast whether adhesive A and others can achieve similar bonding strength and stretching characteristics.

The present study employed particular knitted fabrics that were made of polyester and elastane only. The future work should also cover the use of different types of fabrics, like natural fabrics (cotton, linen) and synthetic mixes, to determine their compatibility with PUR adhesives and their bonding characteristics.

It becomes important to study the effectiveness of the use of PUR adhesives in textiles, as their impact on the environment is another factor that should be assessed. Further studies can be prompted as to how the life cycle of these adhesives-contending from production through use and ends with disposal-may be optimized with regard to sustainability in adhesive bonding operations.

Further Studies: Testing bonded fabrics for a long duration under various climatic conditions like humidity, temperature variations, and effect of UV light, etc., would help in knowing the actual durability of the adhesive bonds used in the fabric.

It could also be made better in future studies with the use of optimization techniques, such as machine learning optimization techniques or genetic optimization techniques. This could improve upon the state-of-the-art methods used in determining the conditions of bonding.

REFERENCES

[1] V. D. Gerda Mikalauskaite, "Investigation of the Influence of Bonding and Thermal Ageing Duration on the Peeling Strength of Knitted Materials Bonds," *Journal of materials science* , 2019.

[2] Erdal Ekinci, Irina Nowikowa and Andrea Ehrmann, "Experimental Study Of Gluing as A Joining Method For Garments," 2020.

[3] Cheng-Hung Chung, Wen-Chang Shih and Wei-Ming Chiu, "Synthesis, characterization and properties of biomass and carbon dioxide derived polyurethane reactive hot-melt adhesives," *Journal of E-Polymer* , 2019.

[4] P. Ambhore, U. Mogera, B. Vaisband, U. Shah, T. Fisher, M. Goorsky and S. S. Iyer, "PowerTherm Attach Process for Power Delivery and Heat Extraction in the Silicon-Interconnect Fabric Using Thermocompression Bonding," in *IEE*, 2019.

[5] S.-Y. Jung, H. E. Hong and K.-W. Paik, "A Study on the Cu-Rod Anisotropic Conductive Films (ACFs) for Flex-on-Fabric (FOF) Interconnections Using an Ultrasonic Bonding Method," 2023.

[6] Antonio Piqueras, Miguel Angel Martinez, Juana Abejonar and Jose Luddey Marulanda, "Characterization a polyurethane-based reactive hot melt adhesive for applications in materials," 2019.

[7] Dong Leia, Jing Caoc, Shuo Chena and Wen Chang Shihd, " PPC-based Reactive Hot Melt Polyurethane Adhesive Efficient Glues for Multiple Types of Substrates," *Springer-Verlag GmbH Germany,* 2018.

[8] Maria Alejandra Moyano and C. Hernandez, "Enhanced Green Strength in a Polycarbonate Polyol-Based Reactive Polyurethane Hot-Melt Adhesive," *Polymers,* 2024.

[9] M. A. Moyano and E. Orgiles, "Reactive polyurethane hot-melt adhesives with high biogenic carbon content," *Journal of Adhesion* , 2023.

[10] Biru Shi and Xiaoling Xu, "Comparison and investigation of H-bond assisted reusable PU adhesives with high shear strength," *Progress in Organic Coatings* , 2024.

[11] Chenyang Fan and Jiayi Tu, "Study on Preparation and Performance of Polyurethane Hot," *Advances in Engineering Technology Research ,* 2023.

[12] Li Sun and Wei Zhang, "Reactive polyurethane hot melt adhesives based on polycarbonate and sebacic acid-based polyester polyols," *Journal of Adhesion Science and Technology,* 2022.

[13] Sharath Chandra, Rashmi Shetty and Sampath Kumar, "Tribological properties of CNT-filled epoxy-carbon fabric composites Optimization and modelling by machine learning," *Journal of Materials Research and Technology,* 2023.

[14] Hanani Abdul Wahab, Anika Zafiah, M.F.L Abdullah and Munirah Abdullah, "Design of Experiment for Sound Absorption Materials of Microporous Polymer," *2019 International Conference on Information Science and Communication Technology (ICISCT) ,* 2019.

[15] Gokarna Aryal, Lash Mapa and Sai Kiran Camsarapalli, "Effect of Variables and their Interactions on RFID Tag Readability on a Conveyor Belt," *IEEE,* 2010.

[16] Janaka R. Gamage , Anjali K.M. DeSilva, Dimitrios Chantzis and Mohammad Antar, "Sustainable machining Process energy optimisation of wire electrodischarge machining of Inconel and titanium superalloys," 2017.

[17] Y. M. A. Bnar Hiwa, "Evaluation of tensile properties of Meriz fiber reinforced epoxy composites using Taguchi method," *Journal of Results in Engineering,* 2023.

[18] Hafsa Jamshaid, Naseer Ahmad, Uzair Hussain and Rajesh Mishra, "Parametric optimization of durable sheeting fabric using Taguchi Grey Relational Analysi," *Journal of King Saud University – Science,* 2022.

[19] M. Venkata Ramana, Krishna Mohana Rao, Bidya Sagar and Ravi Kumar, "Optimization of surface roughness and tool wear in sustainable dry turning of Iron based Nickel A286 alloy using Taguchi's method," *Journal of cleaner Engineering and Technology,* 2020.

[20] L. M. k. P. Jayaramana, "Multi-response Optimization of Machining Parameters of Turning AA6063 T6 Aluminium Alloy using Grey Relational Analysis in Taguchi Method," 2014.

[21] X.-S. Yang, "Nature-Inspired Optimization Algorithms", 2014.

[22] K. M. Tom De Weer, "A multi-objective framework for Pareto frontier exploration of lattice structures," *Structural and Multidisciplinary Optimization,* 2023.

[23] M. Ramachandran, "Study of Compression Molding of GFRP using Grey Relational Analysis," *International Journal on Design & Manufacturing Technologies,* 2014.

[24] Y. W. Gang Lei1, "Optimal Crash Analysis of Vehicle Based on DOE," *IEEE,* 2021.

[25] C.S. Chien, C.W. Chien and H.F.Liee, "Taguchi DoE for Solder Voids Reduction," in *IEEE*, 2018.

[26] H. K. A. S. Wanigasundara, R. M. H. C. Rathnayake, M. Y. A. Perera and R. M. V. S. Ratnayake, "Investigating the bond strength of oxygen plasma-treated finished cotton-based fabric bonded with thermoplastic polyurethane film adhesive," in *IEEE*, 2023.

[27] M. N. S. Chen, "Determination of Bond Strengths in Non-woven Fabrics: a Combined Experimentaland Computational Approach," 2017.

[28] Xiaojian Liu, Nan Kang, Cui Jing, Lei Shi, Yawei Liu and Mengmeng Yin, "Optimization of Gold Wire Bonding Process for Microwave Components by DOE Method," *19th International Conference on Electronic Packaging Technology,* 2018.

[29] Shervan Babamohammadi, William George Davies and Salman Masoudi Soltani, "Probing into the interactions among operating variables in blue hydrogen production: A new approach via design of experiments (DoE)," *Journal of Gas Science and Engineering,* 2023.

[30] Mahmoud Naim, Mahdi Chemkhi,Julien Kauffmann and Akram Alhussein, "Taguchi DoE analysis and characterization of 17-4 PH stainless steel parts produced by material extrusion (MEX) process," *Journal of Advances in Industrial and Manufacturing Engineering,* 2023.

[31] F. T. Tolgahan Ermergen, "Investigation of DOE model analyses for open atmosphere laser polishing of additively manufactured Ti-6Al-4V samples by using ANOVA," *Journal of Optics and Laser Technology,* 2023.

[32] I.C. Goss, T.S. Rosendo, M.D. Tier b and A. Wiedenhoft, "Shear strength optimization for FSSW AA6060-T5 joints by Taguchi and full factorial design," *Journal of material science and technology* , 2020.

[33] Ilesanmi Daniyana, Rumbidzai Muvunzia, Khumbulani Mpofua and Adefemi Adeodub, "Optimisation of Process Parameters during the Turning Operation of Titanium Alloy (Ti6Al4V) using the Taguchi Methodology," in *16th CIRP Conference on Intelligent Computation in Manufacturing Engineering,* , 2023.

[34] Xiaohua Zhao, Lina Lin , Xiaorong Xiong and Mohammad Mahbubul Hassan, "The optimization of whiteness of polyester fabric treated with nanoparticles of 2,2′-(vinylenedi-p-phenylene)bis-benzoxazole (OB-1) by the Taguchi method," *Journal of Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 2023.

[35] K. Zoschke, T. Fischer, H. Oppermann and K.-D. Lang, "Temporary handling technology for advanced wafer level packaging applications based on adhesive bonding and laser assisted de-bonding," in *IEEE*, 2014.

[36] S. Mu, J. Yin, J. Yuan and S. Ng, "Design of experiments for simulation models with stochastic constraints," IEEE, 2019.

[37] O. Tumova, L. Kupka and P. Netolicky, "Design of Experiments approach and its application in the evaluation of experiments," in *IEEE*, 2018.

[38] M. T. MacNicoll, T. Dewhurst, P. R. Akers and D. A. Capotosto, "A Design of Experiments based approach to engineering a robust mooring system for a submerged ADCP," in *IEEE*, 2018.

[39] J. Devaraj, A. Ziout and J. A. Qudeiri, "Optimization of Welding Dissimilar sheet metals using Taguchi and Grey based Taguchi Methods," in *IEEE*, 2022.

[40] M. Abolghasemi, A. Ghaheri, S. M. Saghin and S. E. Afjei, "Multi-Objective Optimization of an Axial-Flux Magnetic Gear Using Taguchi Method," in *IEEE*, 2023.