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Review Article

Thermal Bonding of Nonwovens

A Thambidurai[1]*, S Ariharasudhan[2] and S Sundaresan[3]

[1]Assistant Professor, Department of Fashion Technology, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

[2]Assistant Professor, Department of Textile Technology, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

[3]Associate Professor, Department of Textile Technology, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

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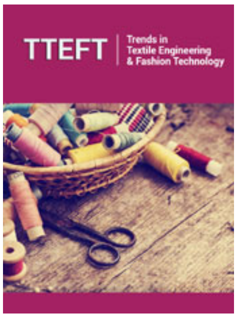

***Corresponding author:** A Thambidurai, Assistant Professor, Department of Fashion Technology, Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

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Abstract

The growing demand for innovative textile products has accelerated advancements in thermal bonding, making it a key technology in nonwoven fabric manufacturing. Improvements in raw materials, web formation, and production speeds have enhanced its effectiveness for both durable and disposable nonwovens. Using thermoplastic fibres, processes like heated calendar rolls and ovens ensure high production efficiency. Innovations in thermoplastic and thermoset materials, such as powders, films, and hot melt compounds, along with techniques like point-bonding, through-air bonding, and belt bonding, have expanded the range of achievable products, solidifying thermal bonding's importance in the industry.

Keywords: Nonwoven fabric; Non-thermoplastic fibers; Thermoplastic fibers; Binder fibers

Introduction

Thermal bonding, developed in the 1940s, has become a key process in nonwoven fabric manufacturing due to its cost-effectiveness and lower energy consumption compared to traditional methods. It is versatile, bonding various web types such as dry-laid, polymer-laid, wet-laid, and multi-layer materials. The process was first introduced by Reed, who heated a web of thermoplastic and non-thermoplastic fibers to the melting or softening point of the thermoplastic fibers, then cooled it to solidify the bonding areas. Early thermal bonding used rayon fibers blended with binder materials like plasticized cellulose acetate or vinyl chloride. A carded web was produced, then hot-calendered and cooled to form a thin, strong, and dense product. Although the binder fibers were costly, thermal bonding offered significant economic advantages through energy savings over chemical bonding methods, which require extensive water evaporation. These benefits, alongside high production rates, have made thermal bonding a preferred choice in various industries [1].

Principle of thermal bonding

Thermal bonding involves a thermoplastic component, such as homofil fibre, powder, film, hot melt, or bicomponent fibre sheath. Heat is applied until the thermoplastic melts, allowing it to flow to fibre crossover points, where bonding regions form and solidify upon cooling. No chemical reaction occurs between the binder and base fibre at these sites. The binder forms an adhesive bond via surface tension and capillary action, or a mechanical bond through thermal shrinkage. If both materials melt, inter-diffusion may occur, creating cohesive bonds when compatible polymers are present [2].

Bonding process

Thermal bonding can be achieved through various methods. In through-air bonding, hot air melts fibres at contact points to form bonds. Infrared (IR) bonding uses infrared light to heat fibres and induce partial melting. Ultrasonic bonding relies on ultrasound friction to melt fibres at contact points. Thermal point bonding involves passing a preformed web between heated calendar rolls, smooth or patterned, where bonds form at fibre crossover points or raised areas. Regardless of the method, the process involves heating, bonding, and cooling fibres. This discussion will focus on thermal point bonding and its impact on fabric properties [3].

Raw materials

Thermally bonded fabrics are made from either entirely thermoplastic materials or blends containing fibres that do not soften or flow upon heating. The non-binder component is referred to as the base fibre, with various types used commercially. The binder fibre typically makes up 5-50% of the fibre weight, depending on the desired physical properties of the final product.

Base fibres types

The base fibre determines key physical, chemical, and mechanical properties of the fabric, including dyeing characteristics, flame resistance, tensile strength, hydrolytic resistance, and biodegradability. Common base fibres include natural fibres (e.g., regenerated cellulosic, bast, vegetable, and protein fibres like wool), synthetic fibres (e.g., polyester, polypropylene, acrylic, nylon, aramid), mineral fibres (e.g., glass and silica), and metallic fibres. The base fibre may also form the core of a bicomponent fibre, with the binder as the sheath [4].

Binder materials

Binder components are available in various forms, including fibre or filament (homogeneous or bicomponent), powder, film, low-melt webs, and hot melts. The binder's physical form influences its distribution in the fibre matrix, significantly affecting fabric properties. The binder content also plays a crucial role in the final fabric characteristics. If the binder exceeds 50% of the blend, the fabric behaves like reinforced plastic. At 10% binder content, the fabric is bulky, porous, and flexible, with relatively low strength [5]. To minimise energy costs, binder fibres should have a high melting speed, low shrinkage, and a narrow melting point range. The most used thermoplastic binder polymers are listed in the Table 1.

Table 1: Thermal transition temperature of common thermoplastic binder material.

Fibre Type	Glass Transition Temperature (Tg) (°C)	Melting Temperature (Tm) (°C)
Polyvinyl chloride (PVC)	91	200-215
Polyamide (PA)	50	210-230
Polyester (PET)	69	245-265
Polypropylene (PP)	-18	160-175
Low Density Polyethylene (LDPE)	-110	115

Many materials that are used as a binder for thermally bonded nonwovens can be apply by following methods in production.

1. Binding fibers
2. Binding powder
3. Binding web

Binding fibers

Single-component and bi-component fibres are commonly used as binder fibres in thermal bonding of nonwovens. Single-component fibres are simple, cost-effective, and readily available. The type of bond formed depends on factors such as fibre chemistry, morphology, linear density, staple length, crimp, and processing conditions. A key disadvantage of using 100% single-component fibres is the narrow temperature range required for bonding - too low a temperature results in weak bonds, while too high a temperature causes excessive melting, compromising the web's structure. Bi-component fibres offer a wider bonding temperature range, typically up to 25 °C. During bonding, the high-melting portion of the fibre maintains web integrity, while the low-melting portion bonds with other fibres at crossover points. This results in a product with bulk and exceptional softness.

Binding powder

Powdered polymers, especially powdered polyethylene, are commonly used in thermal bonding of nonwovens. These binders can be applied during or after web formation. A thermoplastic polymer with a low softening temperature is preferred, requiring minimal heat exposure to melt and fuse the powder. Ideal powders should have low melt viscosity and a narrow melt-to-solid temperature range. Polymers such as polyethylene, low molecular weight polyamide, and vinyl chloride-vinyl acetate copolymers are typically used. However, this method is limited by challenges in obtaining suitable particle sizes and achieving uniform powder distribution. Powder bonding is ideal for lightweight webs requiring soft handles or open structures, and is used in applications such as feminine hygiene, adult incontinence, medical and automotive products, wipes, computer disks, apparel, and shoe composites [6].

Binding web

A low-melting-point thermoplastic fabric is placed between webs and, during thermal bonding between calender rolls, it melts completely, bonding the webs together. The resulting nonwoven is soft and bulky. Thermoplastic coatings and hot melt print bonding have been used in controlled porosity filters, impermeable membranes, and other products, though this bonding method is not expected to become widely significant [7].

Methods of Thermal Bonding

1. Hot calendering
2. Belt calendering
3. Through-air thermal bonding

4. Ultrasonic bonding
5. Radiant-heat bonding, etc.

Hot calendering

Thermal bonding uses heat to melt or soften components in a web to create bonds. Heat can be applied through conduction, convection, or radiation. One common method, thermal calender bonding, involves passing a fibrous web with thermoplastic components through a heated calender nip formed by two rolls. Multi-nip calenders are used for varying web weights and bonding levels. Both rolls are heated above the binder's melting point to ensure effective heat transfer. As the web passes through, the binder softens and flows around the base fibres, forming bonds at fibre crossover points, which solidify upon cooling. Calender bonding is ideal for light and medium-weight webs, but thicker webs may experience uneven heat transfer. Infra-red pre-heating can improve efficiency. Typical applications include lightweight webs (25-30g/m^2) for medical and hygiene products and medium-weight webs (100g/m^2) for interlining and filtration. Bonding quality depends on temperature, pressure, speed, and dwell time. The three main types of hot calendering are area bonding, point bonding, and embossing. The degree of bonding varies, with area bonding achieving 100%, while point bonding and embossing result in less [8].

Area bonding: In area bonding, a calender with a hot metal roll is opposed by a wool felt, cotton, or special composition roll. Depending on the web weight and desired bonding degree, two, three, or four-roll calenders may be used. The three-roll calender has the heated roll in the middle, while the four-roll calender places heated rolls at the top and bottom, with composition rolls in the centre. The binder fibres used provide bonding at all crossover points between the carrier and binder fibres, resulting in a smooth, thin, and stiff product, commonly used in electrical insulation and coating substrates. The process can lead to uneven bonding, with the outer surface more bonded than the inner area, particularly as product weight exceeds 35g/m^2. To correct this, heat, speed, or binder/carrier fibre ratio can be adjusted. The two-roll calender is used for low-to-medium weight products, the three-roll for special effects, and the four-roll offers the widest range of materials due to greater heat application flexibility.

Factors influencing area-bonding hot calendering include:

- Heat: Applied to the metal roll by conduction or restrictive heating, with composition rolls gaining heat from contact with the metal roll.
- Pressure: Heat makes the binder thermoplastic, while pressure forces the binder to flow around the carrier fibres, enhancing mechanical bonding.
- Speed: The speed of the nonwoven through the calender, combined with heat and pressure, determines the degree of bonding and throughput rate, affecting product cost.
- Roll combination: A metal roll and felt roll combination ensures uniform pressure application.
- Cooling rolls: Cooling rolls prevent stretching and stress from occurring after the calendering stage, avoiding shrinkage during post-heat treatments.

Point bonding: Point-bond hot calendering is commonly used for bonding disposables such as diapers, sanitary products, and medical items. This method involves a two-roll nip, consisting of a heated male-patterned metal roll and a smooth or patterned roll, which may or may not be heated. The web is fed through an apron into the calender nip, where the fibre temperature rises, causing tackiness and melting. Fibre segments caught between the engraved points and the smooth roll bond together, with heating times typically in the millisecond range. Fabric properties depend on process temperature, pressure, contact time, quench rate, and calender pattern. Experimental results show that for a given nip line pressure and calendering speed, breaking strength peaks at a critical bonding temperature. This critical temperature varies with calendering speed, while maintaining constant nip line pressure [9].

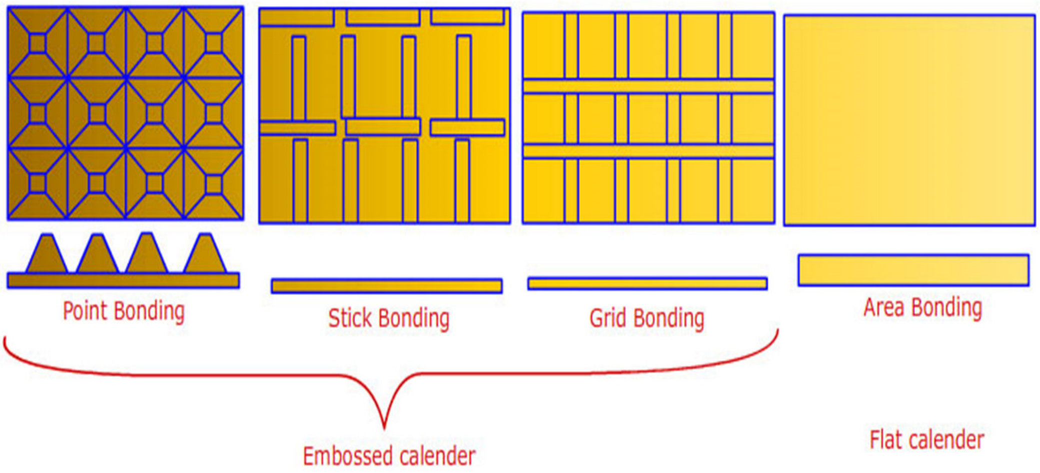

Figure 1: Methods of thermal bonding.

Embossing or novonette system: This method, a sculptured area-bond hot calendering, creates a three-dimensional area bond, producing a “bulky but thin” product with customizable construction, depending on the embossing roll faces. The calender roll combination consists of a male-patterned heatable metal roll and a matching female-patterned felt roll. In point bonding, webs are embossed by passing between an engraved calender roller and a smooth roller, creating a fabric with an impression on one side and a smooth surface on the other. Both rollers may have identical patterns, with raised areas on one roller aligning with raised areas on the other, or raised areas on one aligning with grooves on the other. Accurate roller positioning is critical for pattern definition, making it costly and difficult. The Novonette pattern, developed by Kendall Co., uses two helically engraved rollers with lands and grooves. This design ensures even pressure distribution, eliminating the need for precise roller alignment. The width of lands and grooves and the angle of the rollers can be adjusted to modify the fabric’s physical and aesthetic properties. As the web passes through heated rollers under pressure, a repeating pattern forms, with varying pressure zones resulting in different bonding levels. Factors like mechanical process conditions and web structure influence the calendering effect (Figure 1) [10].

Belt calendering

Belt calendering is a modified form of roller calendering, differing in nip time and applied pressure. While roller calendering has heating times of milliseconds, belt bonding extends nip time to 1-10 seconds, with pressure typically not exceeding 9N/mm compared to 35-260N/mm in roller calendering. The belt bonder consists of a heated roller (40-250cm in diameter) coated with PTFE, and a heat-resistant silicone rubber blanket covering up to 90% of the roller. The fabric bonds as it passes between the roller and blanket under heat and pressure, with pressure adjusted by modifying blanket tension and exit guide roller pressure. The result is a less dense, paper-like fabric compared to roller-calendered products. Belt calendering allows for the use of binders with sharp melting points that are difficult to manage in roller calenders. Both area and point bonding are possible, with embossing achieved via a roller post-belt section. Double drum bonders can process thicker fabrics, with working widths up to 6m and speeds up to 100m/min.

Through-air bonding

Through-air thermal bonding applies hot air to the surface of nonwoven fabric, with the air being drawn through the fabric by negative pressure, rather than being pushed through like in conventional hot air ovens. This method ensures rapid and even heat transfer, minimizing fabric distortion. Binders used include crystalline binder fibers, bi-component binder fibers, and powders. When crystalline fibers or powders are used, the binder melts completely and forms droplets throughout the fabric, bonding upon cooling. For sheath/core binder fibers, the sheath is the binder and the core is the carrier fiber. Products made using through-air bonding are bulky, soft, strong, extensible, breathable, and absorbent. After through-air bonding, cold calendering results in a product that is softer, more flexible, and more extensible than one processed with hot calendering.

Through-air bonding can be done using:

1. Perforated drum or rotary systems
2. Perforated conveyor or flatbed systems
3. Impingement bonding (air jetting system).

Perforated drum-through-air bonding: In this method, a web wraps around a porous drum for 300° of its circumferences, with a fixed shield inside. Heated air is drawn through the web by suction from a rotary fan, providing high flow efficiency. The drum’s open area, depending on perforation size and shape, can reach up to 48%, or 75% with square perforations for special applications. It processes webs ranging from 10g/m^2 to 3000g/m^2, with heating by steam, thermal oil, gas, hot water, or electricity. Process speeds of up to 300m/min are achievable. Advantages over belt methods include a compact design, reduced energy consumption, and automatic heat recovery. Perforated drums range from 1000 to 3500mm in diameter, with working widths from 400 to 7000mm. One- or two-drum units are common, though multi-drum lines exist. Some designs use a calibrating unit with pressure rolls to produce webs with specific thickness, high tensile strength, and smooth surfaces. Perforated drums with up to 96% open area are used for low-air-permeability webs, enabling high production speeds (>1000m/min) and large working widths (up to 10m).

Perforated conveyor-through-air bonding: In flat conveyor systems, the web is transported without suction draught, enabling the bonding of voluminous nonwoven fabrics, such as airlaid waddings. Thickness changes are influenced by thermal shrinkage and unrestricted fibre shrinkage, making bicomponent fibres with low shrinkage properties ideal. A uniform air flow and temperature distribution across the working width are crucial to prevent uneven shrinkage and bonding. This system is especially suited for bulky, low-density webs.

Impingement bonding (Air jetting system): Impingement systems, traditionally used for drying paper products, can also be adapted for thermal bonding of nonwovens. In air jetting systems, hot air is blown onto the web at speeds up to 40m/s, deflected at a 90° angle to create a flow parallel to the surface. In double-sided air jetting, the web floats on the bottom air flow and both sides are bonded, but less effective heating limits bonding within the cross-section. Compared to through-air bonding, air jetting has a heat transfer ratio of 3:1. This method is ideal for products requiring pile raising and is commonly used in perforated belt systems.

Ultrasonic bonding

Ultrasonic bonding applies rapidly alternating compressive forces to localized areas of fibers, converting stress into thermal energy that softens the fibers. As the fibers cool, bond points form. This method is ideal for spot or patterned bonding of mechanically bonded materials, with synthetic fibers being self-bonding. For natural fibers, synthetic fibers must be blended. Fabrics produced are soft, breathable, absorbent, and strong, commonly used in patterned composites and laminates like quilts and outdoor jackets.

Radiant heat bonding

Radiant heat bonding uses infrared energy to heat the web, melting the binder without affecting the carrier fibers. Bonding occurs as the binder solidifies after the heat source is removed. This method is cost-effective, especially for powder-bonded nonwovens, and offers versatility with lower shipping costs, as post-calendared rolls can be reactivated by heat. Products made are soft, open, absorbent, and low-to-medium strength, suitable for laminated composites.

Conclusion

Thermal bonding is more energy-efficient, environmentally friendly, and cost-effective than latex bonding. It enables the production of a wide range of products, with properties varying from nonporous, thin, non-extensible, and non-absorbent to open, bulky, extensible, and absorbent, depending on the chosen processing method. Recent advancements in thermal bonding include innovations in raw materials, web formation techniques, and higher production speeds, further enhancing the versatility and efficiency of the process. These developments allow for the creation of both durable and disposable nonwovens with improved performance characteristics. All thermal bonding methods provide robust bond points, resistant to harsh environments and various solvents, ensuring reliability and durability in diverse applications.

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