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5.2.2. Through-air bonding...

5.2.3. Calendar bonding...

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7.1.3. IR heating...
PREFACE

This book is a guide through the chemical and thermal technologies of nonwovens. The text contains the fundamental concepts of subject for forth and fifth year of course “nonwovens” study.

The content of this book cannot be knowledge standard for examine. This knowledge shall expand due to the diploma work and it relates to other subjects of “nonwovens” course, especially the subjects: Polymeric binders and Material engineering of nonwovens.

1. NONWOVENS IN GENERAL

1.1. Definition

INDA definition:
Nonwoven is a sheet, web, or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into the yarns, and that are bonded to each other by any of several means.

Notes:
1. To distinguish nonwovens from papers, a material shall be defined as a nonwoven if:
   a) More than 50% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300; or
   b) More than 30% by mass of its fibrous content is made up of fibers as in “a” above and meets one or both of the following criteria:
      i. Length to diameter ratio mare than 600.
      ii. Density of the fabrics is less than 0.4 g/cm³.
2. Bonding methods may include any of the following means or any combination thereof, including but not limited to:
   a) Adding and adhesive.
   b) Thermally fusing the fibers or filaments to each other or to other meltable fibers or powders.
   c) Fusing fibers by first dissolving, then reinforcing their surfaces.
   d) Creating physical tangles among the fibers.
   e) Stitching the fibers or filaments in place.
3. A nonwoven may be a structural component of a composite.
4. Nonwoven structures may incorporate monofilaments or yearns.

1.2. Production of nonwovens

The world production of nonwovens during the year of 2001 was 3,85 millions of tons, i.e. 93 milliards of square meters worth more then 14 milliards of dollars. During the years of 1991-2001, the growth rates of nonwoven production achieve 7,5 % worldwide. The worldwide production in the different areas of world including estimated progression by the year 2006 [Study Examines Nonwovens’ Past and Future, new INDA report..., Nonwovens Industry 33 (2002), 4, pp. 179-180]:

The total world production is shown in Table 1.1.
Table 1.1: Worldwide production of nonwovens

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>North America, Europe a Japan</td>
<td>1,45</td>
<td>2,64</td>
<td>3,56</td>
<td>6,4</td>
<td>6,2</td>
</tr>
<tr>
<td>South America</td>
<td>0,09</td>
<td>0,24</td>
<td>0,36</td>
<td>10,3</td>
<td>8,5</td>
</tr>
<tr>
<td>Asie-Pacifik</td>
<td>0,22</td>
<td>0,46</td>
<td>1,08</td>
<td>11,2</td>
<td>10,7</td>
</tr>
<tr>
<td>Middle East</td>
<td>0,04</td>
<td>0,17</td>
<td>0,34</td>
<td>15,6</td>
<td>15,0</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>0,06</td>
<td>0,16</td>
<td>0,29</td>
<td>10,5</td>
<td>11,3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,86</strong></td>
<td><strong>3,85</strong></td>
<td><strong>5,63</strong></td>
<td><strong>7,5</strong></td>
<td><strong>7,6</strong></td>
</tr>
</tbody>
</table>

Table 1.2: Used technologies of nonwoven production:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spun laid</td>
<td>486</td>
<td>1444</td>
<td>2229</td>
<td>11,6</td>
<td>9,0</td>
</tr>
<tr>
<td>Carded</td>
<td>1182</td>
<td>1964</td>
<td>2632</td>
<td>5,2</td>
<td>6,2</td>
</tr>
<tr>
<td>Air laid</td>
<td>92</td>
<td>276</td>
<td>567</td>
<td>11,6</td>
<td>15,5</td>
</tr>
<tr>
<td>Wet laid</td>
<td>102</td>
<td>161</td>
<td>202</td>
<td>4,7</td>
<td>4,6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1862</strong></td>
<td><strong>3845</strong></td>
<td><strong>5630</strong></td>
<td><strong>7,5</strong></td>
<td><strong>7,6</strong></td>
</tr>
</tbody>
</table>

Table 1.3: Fibers for nonwoven production

<table>
<thead>
<tr>
<th>Fibers for nonwovens</th>
<th>Millions of tons 2001</th>
<th>Millions of tons 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>0,87</td>
<td>1,2</td>
</tr>
<tr>
<td>Polyester</td>
<td>0,6</td>
<td>0,77</td>
</tr>
<tr>
<td>Wood pulp</td>
<td>0,38</td>
<td>?</td>
</tr>
<tr>
<td>Other including bicomponents</td>
<td>0,29</td>
<td>?</td>
</tr>
<tr>
<td>Viscose</td>
<td>0,24</td>
<td>?</td>
</tr>
<tr>
<td>Cotton and other natural fibers</td>
<td>0,07</td>
<td>?</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,4</strong></td>
<td><strong>3,33</strong></td>
</tr>
</tbody>
</table>

The spun laid (spun bond and melt blown) and air laid present the most of technological expansions. In the year 2000, the spun bond technology achieved 50% of European nonwoven production. Renascence of air laid technology is due to high production rate, low costs and uniform products. Reduced chemical bonding technology caused less growth rate of carded technology. Stitch bonding technology evolves successfully. The growth rates of nonwoven production are extremely high when compared with any other industry.
2. POLYMERIC AND FIBROUS PROPERTIES WITH RESPECT TO THERMAL PROCESS

According to polymeric constants (melting temperature, thermal endurance) the conditions of thermal process are chosen. Potential changes into the polymers and fibers can be useful but also it has to be suppressed. The desired change can be the compression and the rigidity of needle punched nonwovens due to the thermo-shrinking fibers. The undesirable changes may be thermo-destruction of polymer, reduction of polymerization degree, change of crystallinity or undesirable thermo-shrinking giving rise to the thickness reduction or irregularity.

2.1. Bicomponent fibers

The typical bicomponent versions are generally as follows:

**Side-by-side fibers**

Side-by-side fibers are usually used as self-bonding fibers. Bicomponent fiber is created by two polymers within a filament having a different strain level or shrinkage tendency. Higher processing speeds, reduced equipment cost, more bulk and improved continuity of process are among the advantages seen with this technology.

**Sheath/core fibers**

- A first type of sheath/core is self-bonding fibers consisting of a low melting temperature sheath and a higher melting temperature core. Common sheath/core alternatives in such applications include PE/PP, PE/PET, Co-PET/PET, and PP/PET. These products are used in 100% form as well as in blends with homopolymer filaments.
- A second type of sheath/core is filled fibers consisting of a core product produced from recycled material, conductive material or other material that is covered by a sheath that possesses desired aesthetics or other properties.
- A third type of sheath/core is a sheath polymer containing expensive additives or other attributes primarily useful on the surface of filaments.

**Tipped yarns**

Tipped products are used to produce special aesthetics, bonding, or other properties.

**Microfibers**

Microfibers can be produced by bicomponent techniques in which the fibers are either caused by split, or one of the two components is dissolved or melted away. These techniques have long been known to be capable of producing much smaller fibers than with homopolymer techniques. Some examples of such fibers are:
- Filaments consisting of alternating segments (pies or stripes) of two different polymers that break apart during downstream processing.
- Filaments consisting of a sea component and an island component, with the sea component dissolved or melted away in subsequent processing. These products have usually been staple fibers with the sea dissolved away in non-woven fabrics. The use of hydroentangling to break the islands apart from the sea also offers promising potential.

**Mixed fibers**

Examples of some applications include the following:
– Color mixes to produce desired aesthetics.
– Denier and cross-section mixes to produce higher bulk or other desired aesthetics.
– Mixes of homopolymer filaments with bicomponents at varying levels to control certain fabric properties such as bonding strength. Some useful results are also being obtained by mixing of bicomponent cross-sections to obtain specific fiber or fabric properties.

![Figure 2.1: The typical bicomponent alternatives](image1)

![Figure 2.2: Bicomponent fiber. Sheath/core 50/50 PE/PP.](image2)
2.2. Thermal constants

The important thermal constants are temperatures between two physical states of polymers; i.e.

![Figure 2.3: Bicomponent fiber. Islands in a sea.](image)

![Figure 2.4: Physical states of polymers. $T_g$ is glass temperature and $T_f$ is plastic flow temperature.](image)

**Glass temperature $T_g$.**

Below this temperature, the polymer is hard, fragile and less deformable. The product lying in the glass state loses textile character. It is why the choosing of polymer is dependent on $T_g$ that shall be lower than the production temperature. Till seventieth years, the mixture of polymers with softening agents solved this problem. The softening agents were chemicals lowering concentration of secondary bonds between macromolecules and $T_g$ respectively. They were aggressive chemicals that ejected from the polymer to ambient.

Due to copolymers a lot of bonding agents with low $T_g$ is available.
Plastic flow temperature $T_f$.
$T_f$ sets the minimal melting temperature. $T_f$ can be above decomposition temperature and polymer is not useable. The depolymerization, oxidation and other chemical reactions can proceed in the melting.

**Viscosity**
Viscosity is a function of temperature and polymerization degree.

**Specific Heats**
- Specific Heats $c_{sp}$ of polymers set heat consumption during the polymer heating.
- Latent heat $c_l$ of crystallite fusion can be utilized to crystallinity degree assessment.

*Table 2.1: Thermal constants of polymers*

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$c_{sp}$ [kJ.K⁻¹.kg⁻¹]</th>
<th>$c_l$ (*) [kJ.kg⁻¹]</th>
<th>$T_g$ [°C]</th>
<th>$T_f$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>1,5 – 2,5</td>
<td>ca. 50</td>
<td>-18 – -35</td>
<td>155</td>
</tr>
<tr>
<td>Polyamide 6</td>
<td>1,5 – 2,5</td>
<td>ca. 50</td>
<td>55</td>
<td>215</td>
</tr>
<tr>
<td>Polyethyleneterephthalate</td>
<td>1,5 – 2,5</td>
<td>ca. 50</td>
<td>85</td>
<td>256</td>
</tr>
<tr>
<td>For comparison H₂O</td>
<td>4,184</td>
<td>2257 (**)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(*) - semi-crystalline polymers
(**) - evaporation heat

The difference of heat consumption between the polymer melting and water evaporation is evident.

### 2.3. Fibrous thermo-shrinking

Due to the heat, intermolecular bindings of drown fibers release and macromolecules create statistical coil then they change their long. This process calls shrinking.

Shrinking degree in percents is given by follows:
1. Fiber history: type of polymer, molecular weight, spinning condition, drawing ratio, rate and temperature of drawing, heat fixing, storage time and conditions.
2. Temperature of shrinking
3. Shrinking time
4. Shrinking medium (water, air, etc.)
5. Tension during the shrinking

Then, the folow parameter can be measured.
1. Shrinking degree (%)
2. Shrinking force
3. Shrinking rate
2.4. Thermal degradation of polymers

Solar radiation, temperature, precipitation and oxygen give a start to an ageing process of the materials, influencing at the same time many of their physical properties. These processes are inevitable in time and are thus simulated by the XENOTEST, an apparatus for accelerated exposure to light and bad weather.

With this apparatus we can make 2 kinds of tests: the first one, called "exposure to the light", simulating the solar effect behind windows, while the second one, called "solidity to the bad weather", simulates the effect of the sun outdoors.

The artificial bad weather simulated by the XENOTEST offers the advantage of well-defined conditions that can be regulated and repeated at any moment. A xenon-radiating instrument produces the radiation that strikes the surface of the test-piece.

The temperature can be regulated up to a maximum of 90°C and the humidity can reach 95%. The rain is simulated by a spray system, while a timer allows us to plan different rain cycles. The leather test-piece is inserted in the XENOTEST together with a blue scale, made of eight standards of coloured wool.

Fastness is valued in this way: when the first perception of a chromatic variation of the test-piece appears, we check if the contrast between the exposed zone and that not exposed is equal to the 4° standard of the gray scale for assessing change of colour. When the chromatic difference is actually equal to the 4° standard of the gray scale, the test is over.

2.5. Detection of polymeric structural changes and thermal constants

2.5.1. DSC

The operation of a Differential Scanning Calorimeter (DSC) is based on measurement of the thermal response of an unknown specimen as compared with a standard when the two are heated uniformly at a constant rate. The DSC consists of a furnace containing two identical crucibles, each of which rests on a thin plate located inside the measurement head. Directly beneath the center of each crucible is the junction of a differential thermocouple. Any difference in temperature of the two specimens is caused by differences in mass, specific heat, heats of reaction, or phase transitions.
Differential Scanning Calorimeter (DSC) measures the amount of energy (heat) absorbed or released by a sample as it is heated, cooled, or held at a constant temperature. Typical applications include determination of melting point temperature and the heat of melting; measurement of the glass transition temperature; curing and crystallization studies; and identification of phase transformations.

Figure 2.6: DSC measurement arrangement

To determine specific heat capacity, a baseline is established by measuring the temperature difference of the two empty crucibles as the temperature is changed at a constant rate over the temperature range of interest. Thermal response records are then acquired for a standard material (usually sapphire) and an unknown under identical conditions. The ratio of
the departure of the standard and unknown from the baseline is then used to calculate the specific heat of the unknown.

**Applications:**
The DSC is used to measure specific heat capacity (100 to 1200°C) and heats of transition as well as to detect the temperature of phase changes and melting points in the range of 20 to 1500°C. Specific heat capacity can be used in conjunction with thermal diffusivity to obtain thermal conductivity.

2.5.2. **DTA**

The DTA uses a dynamic measuring principle. It can measure endothermal and exothermal heat flows between the sample and the reference. These heat flows are result of physical or chemical changes of the samples. Very often a DTA is used for purity measurements of mixtures of metals. This is due to the fact that the melting point changes in dependence to differing amounts of impurities.

![Figure 2.7: DTA diagram.](image)

*Figure 2.7: DTA diagram. T₀ is opening temperature, Tₘ maximal or minimal temperature, T₁ temperature of return to zero line, Tₓ temperature of exothermic process start, Tᵧ temperature of exothermic process end.*

The DTA 404 PC Eos allows determination of such effects between room temperature and 1550°C. Using true state-of-the-art DSC sensors, quantification of transformation energetics is also possible. Incorporating a newly designed electronics and data acquisition system, the DTA 404 PC Eos gives excellent performance at a very attractive price. It is an ideal instrument for research, development and quality control.

**Analysis of**
- Phase transition temperatures
- Transition enthalpies
2.5.3. **TMA**

Thermomechanical Analyzer (TMA) is a computer-controlled laboratory instrument for use in a broad range of application areas. The TMA permits the measurement of dimensional and viscoelastic changes as a function of temperature or time. Typical applications include coefficient of expansion, softening point, glass transition determinations, and modulus measurements.

![TMA Diagram](image)

**Figure 2.8:** TMA diagram. The conventional TMA curve ($L$) is simply a moving average of the length change over one period. The reversing thermal expansivity ($\alpha$) is derived from the ratio of the amplitudes of the length change and temperature change using a discrete Fourier transform. The total rate of length change ($dL/dT$ [300 parts per million = 0.03%]) is simply the derivative of the average length with respect to temperature. As with MT-DSC there is a time lag between the temperature change and the sample response ($\delta$).
In this technique (TMA), dimensional changes in a sample are the primary measurement, while the sample is heated, cooled, or studied at a fixed temperature. A simple schematic figure of a typical TMA instrument is shown below.

The sample sits on a support within the furnace. The changes in length are measured by a sensitive position transducer, normally a Linear Variable Displacement Transducer.
A thermocouple near the sample indicates its temperature. The gas atmosphere through the instrument prevents oxidation and also assists in heat transfer to the sample. Helium is effective in this respect.

The load may be applied by static weights, as above, or by a force motor. The applied load can be programmed to allow a greater range of experiments. The instrument is calibrated for position measurements by heating a sample whose expansion coefficient is accurately known. Aluminium is commonly used, in the form of small machined blocks or cylinders.

Sample sizes are commonly around 5-10 mm in height and width. It is important to prepare samples with clean, flat and parallel faces to avoid artefacts in the recorded curves.

There are a number of approaches to temperature calibration. One method uses small flat pieces of pure metals, e.g. indium, sandwiched between thin discs of quartz glass. Melting of the metal sandwich under the probe with a moderate load results in a sharp displacement of the probe. With care, a multi-layer sandwich can be built up using "fillings" of different metals, so that a multi-point calibration can be obtained in one experiment. The TMA curve for such an experiment is shown below.

Sometimes the required information is about the deformation of the sample, and several types of probe are used for different types of study. A range of typical probes, available with most instruments, is shown below.

![Figure 2.11: TMA instrument. A range of typical probes.](image)
3. POLYMERIC AND FIBROUS PROPERTIES WITH RESPECT TO CHEMICAL PROCESS

3.1. Polymer and co-polymer dispersions

There are three main kinds of binders: butadiene copolymers, acrylates, and vinyl copolymers. The chemical compositions influence Tg, hardness and softness, hydrophobicity and hydrophilicity, elasticity, aging, and dry tensile strength of binders. The higher the Tg, the stiffer the hand and higher the dry tensile strength of binders.

The lower the (T_g) of the monomer units, the softer is the resulting polymer. A sampling of the most common monomers used in the manufacture of latex polymer for nonwoven binders include the following materials:

<table>
<thead>
<tr>
<th>Monomer</th>
<th>Tg(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene</td>
<td>-125</td>
</tr>
<tr>
<td>Butadiene</td>
<td>-78</td>
</tr>
<tr>
<td>Butyl Acrylate</td>
<td>-52</td>
</tr>
<tr>
<td>Ethyl Acrylate</td>
<td>-22</td>
</tr>
<tr>
<td>Vinyl Acetate</td>
<td>+30</td>
</tr>
<tr>
<td>Vinyl Chloride</td>
<td>+80</td>
</tr>
<tr>
<td>Methyl Methacrylate</td>
<td>+105</td>
</tr>
<tr>
<td>Styrene</td>
<td>+105</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>+130</td>
</tr>
</tbody>
</table>

**The butadiene polymers** are cross-linked by polysulphides, and their properties are modified by different copolymers. The butadiene monomers provide elasticity while styrene and acrylonitrile monomers give tensile strength, and oil and solvent resistance, respectively. Their disadvantages are oxidation and discoloration due to residual double bonds in their polymer chains.

**Styrene/Butadiene Rubber (SBR)**

\[-(\text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} - \text{CH}_2 -)_n \quad \text{where } \Phi \text{ denotes a phenyl group}\]

**Butadiene/Acrylonitrile Rubber (NBR)**

\[-(\text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} - \text{CH}_2 -)_n \quad \text{CN}\]

**Acrylic binders** are the most widely used and versatile binders available with various modifications. The properties of acrylic binders differ according to their derivatives and copolymers.

They are frequently copolymerized with styrene, acrylonitrile, vinyl chloride or vinyl acetate, depending on the desirable properties. Some of these properties are hardness from styrene, solvent resistance from acrylonitrile, flame retardancy from vinyl chloride, and cost benefits from vinyl acetate.

The functionality of binders is in the functional groups attached to polymer chains, which influences wet and solvent properties. To modify binder properties, copolymerization with a small amount of monomers with special functionality is performed. The main functionalities in binders are carboxyl and amide side chains.
The carboxyl functionality is related to binders which contain acrylic acid or methacrylic acid by copolymerization. The binders are crosslinkable since the functional group, carboxylic acid, provides sites for crosslinking reactions.

**Acrylates**

\[-\text{CH}_2 - \text{CH} - \text{COOR}\]

**Acrylic Acid**

\[-\text{CH}_2 - \text{CH} - \text{COOH}\]

**Acrylamide**

\[-\text{CH}_2 - \text{CH} - \text{O} = \text{C} = \text{NH}_2\]

**Metholyated Acrylamide**

\[-\text{CH}_2 - \text{CH} - \text{O} = \text{C} - \text{NHCH}_2 \text{OH}\]

**Vinyl copolymers** are two main binders for vinyl copolymers: vinyl chloride and vinyl acetate. Since the vinyl binders are stiff, they are plasticized externally or internally. As internal plasticizers, ethylene and acrylate monomers are used, and external plasticizers consist of vinyl chloride. Due to its low Tg, vinyl acetate is not that stiff, and its advantage is low cost. The chlorides cause yellowing problems. The chemical structures are closely related Tg and stiffness of binders.

**Vinyl acetate**

\[-\text{CH}_2 - \text{CH} - \text{O} \quad \text{O} = \text{C} - \text{CH}_3\]

**Vinyl chloride**

\[-\text{CH}_2 - \text{CH} - \text{Cl}\]
3.2. Crosslinking polymers

Vulcanization of dien

Vulcanization is the process of cross-linking elastomer molecules to make the bulk material harder, less soluble and more durable. The finished product is not sticky like raw rubber, does not harden with cold or soften much except with great heat, is elastic, springing back into shape when deformed instead of remaining deformed as unvulcanized rubber does, is highly resistant to abrasion and to gasoline and most chemicals, and is a good insulator against electricity and heat. Many synthetic rubbers undergo processes of vulcanization, some of which are similar to that applied to natural rubber.

\[
\begin{align*}
-\text{CH} &= \text{CH} - \\
+ &\quad S_x \\
\rightarrow &\quad S_x \\
-\text{CH} &= \text{CH} - \\
\end{align*}
\]

Crosslinking with Organic Peroxide

Crosslinking reaction starts at high temperatures, and it brings to the formation of a three dimensional network by creating bonds between the polymer chains. Peroxide crosslinking may happen in a temperature range varying from 110 to more than 200°C and leads to carbon-to-carbon bonds creation by hydrogen abstraction from the polymer chain.

Crosslinking reaction steps are:

Step 1) Peroxide thermal decomposition

\[
\Delta
\]

\[
\begin{align*}
R^1\text{OOR}^2 \\
\Delta \\
R^1\text{O}^* \\
\end{align*}
\]

Figure 3.1: Illustrates the crosslinking mechanism using peroxide free radical initiation

\[
R^1 - O - O - R^2 \xrightarrow{\Delta} R^1 - O^* + R^2 - O^*
\]

Step 2) Hydrogen abstraction with radical formation on the polymer chain
Figure 3.2: illustrates the crosslinking mechanism using peroxide free radical initiation

\[
R-O^* + \sim\sim C- \sim\sim \rightarrow R-O-H + \sim\sim C- \sim\sim
\]

macro free radical

Step3) Crosslinking reaction by free macroradical recombination

Figure 3.3: illustrates the crosslinking mechanism using peroxide free radical initiation

Carboxyl functionality

This functionality is related to binders which contain acrylic acid or methacrylic acid by copolymerization. The binders are crosslinkable since the functional group, carboxylic. Carboxy-groups with ZnO:
Self-crosslinking polymers

The polymers contain n-methylol functional groups are self-crosslinking polymers. They can react with themselves, and a high crosslink density can be obtained by adding curing resins.

The following comparison of latex binder chemical types provides an indication of the relative performance, as well as the advantages and disadvantages of each type of binder. As indicated, the binder properties can be modified considerably by the presence of co-monomers.

Acrylic: These binders offer the greatest durability, color stability, and dry/wet performance. Acrylic binders have the widest range of fabric hand properties. They can be formulated to vary from very soft (Tg = -40°C) to extremely hard (Tg = 105°C). These binders can be used in virtually all nonwovens applications, although they tend to be more costly. These polymers can be made to cross-link, with substantial improvement in durability.

Styrenated Acrylics: These are tough, hydrophobic binders. The resulting textile hand ranges from soft-to-firm (Tg varies from –20°C to +105°C). These binders can be used in applications where there is a need for some wet strength without crosslinking. The use of this type of latex binder does involve some sacrifice in UV and solvent resistance.

Vinyl Acetate (VAC): The vinyl acetate binders are firm (Tg = +30°C to +40°C); however, they are relatively low cost and find extensive use. They offer good dry strength and toughness, but are somewhat hydrophilic and have a tendency to yellow when subjected to heat.

Vinyl Acrylics: These binders are more hydrophobic than the straight VAC binders. They provide excellent toughness, flexibility, and better color stability. They are the compromise between VAC and acrylic, and can compete on a cost/performance basis. The hand range is limited to intermediate softness (Tg = -10°C) to a firm hand (Tg = +30°C).

Ethylene Vinyl Acetate (EVA): These latex binders have a (Tg range of –20°C to +115°C, which is equivalent to soft ranging to an intermediate textile hand. They exhibit high wet strength, coupled with excellent absorbency. In general, they are less costly than acrylics. They do have a tendency to have more of an odor compared to other binders. They are used primarily in wipes, air-laid pulp fabrics and similar applications.

Styrene-Butadiene (S/B, SB, or styrene butadiene rubber): These binders have an excellent combination of flexibility and toughness. They range in hardness from very soft (Tg
= -30°C) to very firm (Tg = +80°C). However, the (Tg of an SB binder is not strictly comparable to other classes of nonwoven binders. The styrene-to-butadiene ratio (S/B ratio) is the most common method for describing the relative hand resulting from the use of these binders. The higher the styrene content, the firmer the hand. When cross-linked, this class of binder is very hydrophobic and durable. They are affected somewhat by heat and light because of their tendency to oxidize.

**Polyvinyl Chloride (PVC):** The homopolymer of polyvinyl chloride is a very hard, rigid polymer (Tg = +80°C). This polymer must be plasticized to provide flexibility and film-forming properties. Normally, the (PVC) binders used in nonwovens are softened internally by co-polymerizing the vinyl chloride or with softer acrylic monomers. The hand range of most of these polymers is still relatively firm (Tg is greater than the +30°C). Because this type of polymer is quite thermoplastic, it performs well in heat and dielectric sealing applications. This can be an advantage in some uses. Also, the chlorine content of the polymer promotes flame retardancy. This feature is one of the primary benefits of utilizing this type of binder. However, the chlorine also conveys the tendency to yellow upon heat aging, due to elimination of hydrogen chloride from the polymer.

**Ethylene/Vinyl Chloride (EVCI):** Binders in this class have a slightly broader hand range (Tg = 0°C to +30°C) without the external plasticization required of (PVC) binders. The presence of the chlorine again conveys some flame retardancy. These binders exhibit good acid resistance, fair water resistance, and excellent adhesion to synthetic fibers. There is some tendency to yellow upon aging. In essence, this is an internally plasticized (PVC) binder, considering the ethylene monomer to be the softener.

### 3.3. Coagulation methods

Coagulation is impossible, when there is no interaction between two particles. The trajectories of the particles can be divided into 'open' and 'closed' ones, separated by a 'limiting' trajectory. In the absence of interparticle forces it is impossible for a particle to cross a limiting trajectory, thus either two particles (initially at larger distance than corresponds with the limiting trajectory) will never meet or two particles (initially at smaller distance than corresponds with the limiting trajectory) will never be separated.

*Figure 3.4: Polymer dispersion in water stabilized by an anionic surfactant.*
However, when some forces are operative it is possible for an approaching particle to cross the limiting trajectory and coagulation can occur. It can be achieved by the several principles.

1. Removing water by evaporation
2. Freezing of dispersion
3. Change in acidity

\[
R - \text{COO}^- + H^+ \rightarrow R - \text{COOH}
\]

4. Creating of non-dissociating salts

\[
2 R - \text{COO}^- + \text{Ca}^{2+} \rightarrow (R - \text{COO})_2\text{Ca}
\]

5. Using of thermosensibilizers

\[
\text{Zn (NH}_3\text{)}_2 \text{Cl}_2 \xrightarrow{\text{heat}} \text{ZnCl}_2 + 2 \text{NH}_3
\]

4. WEB FORMING METHODS

4.1. Wet-laid methods

Wet-laid nonwovens are nonwovens made by a modified papermaking process. That is, the fibers to be used are suspended in water. A major objective of wet laid nonwoven manufacturing is to produce structures with textile-fabric characteristics, primarily flexibility and strength, at speeds approaching those associate with papermaking. Specialized paper machines are used to separate the water from the fibers to form a uniform sheet of material, which is then bonded and dried. In the roll good industry 5-10% of nonwovens are made by using the wet laid technology.

The wet-laid process has its origins in the manufacture of paper and was developed because paper manufacturers wanted to be able to use uncut, long natural fibers and synthetic fibers in addition to the usual raw materials without changing the process.

Two fundamental reasons account for physical property differences between paper and textiles. The first is the difference in the raw materials each process uses. Papermaking fibers being short and fine are able to pack together into a dense structure. Chemical groups attached to their surfaces are able to form hydrogen bonds with similar groups on neighboring fibers very easily. Textile fibers, on the other hand, tend to be longer, stronger, and relatively inert when compared to papermaking fibers. The second difference is the structure and the way individual fibers are arranged by the process to make a finished product. In paper, the fibers overlap randomly and pack densely. In textiles, there is a repeating unit structure which provides some extensibility in all directions, but which preserves the basic strength and stability of the fabric (whether knit or woven). In light of the characteristics of these raw materials and structure, one would expect paper to be weak, stiff inextensible, smooth, and dense, while textiles would be stronger, softer, bulkier, more drapeable, less smooth and more porous.

Manufacturers of wet-laid nonwovens desire to take advantage of the high production rate (up to 1000m/min) and the ability to blend a variety of fibers from papermaking
technology. On the other hand, they must overcome the difficulties brought on by using textile fibers and producing fabric stiffness in wet-laying if this technology is to compete realistically with textiles and other nonwoven products.

To alter the basic properties of paper, one must attack paper's two problems discussed above (raw material limitations and structure deficiencies). This has been done by including synthetic fibers in the raw materials for wet-laid nonwovens, by bonding the fibers together (rather than weaving, knitting, or relying on hydrogen bonding), and by using new methods of web forming which improve the structure. The strategies have been successful to one degree of another, either separately or in combination, but each introduces problems for the production process.

In theory, any natural or synthetic fiber could be used in the production of wet-laid nonwovens. However, there are practical limitations on the use of many fibers (cost, availability, priorities, etc). Some form of wood pulp is used in virtually all wet-laid nonwovens because of its ease of handling, low cost, opacity, and chemical reactivity. Natural fibers other than wood pulp remain of interest because they have valuable properties for specialized end-uses. They suffer from unstable pricing and supply due to variations in climate, worldwide demand, and availability of competing fibers. Some natural fibers - such as cotton linters, manila hemp and cellulose staple fibers - are also used in wet-laid process.

Synthetic fibers provide specialized properties, uniformity, and constancy of supply which cannot be achieved by natural fibers. Some are used more widely than other for example, bicomponent fibers, which simultaneously provide both a structural element and a thermobonding capability, have been used in specialized materials despite their high cost. Crimped fibers require special dispersion and bonding techniques, but make a very soft and bulky product. Usually 2-30 mm fibers are used in wet laid process; use of rayon and polyester textile fibers with lengths exceeding 1.5 inches has been reported sporadically. "Synthetic wood pulp" made from very short, shear-precipitated polyolefin fibers is available and results in improved wet strength and other properties of wet-laid nonwovens.

Unfortunately, synthetic fibers for use in wet-laid nonwovens are 20 to 50% more expensive than the same fiber in the form of textile staple, because the market is small relative to that for textile fibers, and special handling and cutting are required. Specialty fibers such as low-melting bicomponent fibers are even more expensive, and their total production is too small to allow economies of scale to be fully realized.

In general, man-made fibers are longer, stronger, more uniform, and less compatible with water than natural fibers. Their flexibility and length can mean that they entangle ("flocculate") when they are dispersed in water, which either prevents or limits their use in nonwovens. Flocculation increases with increase in length to diameter ratio which is given as:

\[ \frac{L}{D} = 100 \sqrt{\frac{L}{T_t}} \]

\( L \) = length of fibers in mm  
\( D \) = diameter of fibers in mm  
\( T_t \) = fiber fineness in dtex

Several approaches have been developed to overcome this problem. For example, synthetic fiber manufacturers offer fibers with proprietary chemical surface treatments, which improve dispersion by overcoming the inherent hydrophobicity of the polymers from which the fibers are made.

The general strategy for reducing flocculation of synthetic fiber furnishes is to increase the dilution (decrease the "consistency" of weight percent of fiber in the suspension). Flocculation occurs when concentration of dispersion exceeds critical concentration of dispersion \( C_w \) defined as percentage of fibers in dispersion and given as:
Papermaking generally uses consistencies in the range of 0.3 to 0.7%, but wet-laid nonwovens are produced using consistencies of 0.005 to 0.05%. While this helps to separate the fibers enough to prevent or reduce flocculation, it requires specialized machinery to form and dry the sheet because of so much water. From an empirical case, we know that slightly less than 960,000 gallons of water per hour must be drained through the wire of a hypothetical machine in order to deposit 2000 pounds per hour of wet-laid nonwovens.

For some applications it may be necessary to work with the fiber supplier to resolve compatibility problems between the dispersion finish and other chemicals used in the system. However, mechanical problems are now far more common than chemical ones in the dispersion step. In especially troublesome dispersion problems, low concentrations of natural and synthetic polymers are used to increase suspension viscosity and thus stabilize dispersions for use on papermaking equipment.

There are three characteristic stages in the manufacture of nonwoven bonded fabrics by the wet-laid method:

- Swelling and dispersion of the fiber in water; transport of the suspension on a continuous traveling conveyor
- Continuous web formation on the conveyor as a result of filtration
- Drying and bonding of the web

### 4.2. Spunbonding process (SB)

Spunbond fabrics are produced by depositing extruded, spun filaments onto a collecting belt in a uniform random manner followed by bonding the fibers. The fibers are separated during the web laying process by air jets or electrostatic charges.

The collecting surface is usually perforated to prevent the air stream from deflecting and carrying the fibers in an uncontrolled manner. Bonding imparts strength and integrity to the web by applying heated rolls or hot needles to partially melt the polymer and fuse the fibers together. Since molecular orientation increases the melting point, fibers that are not highly drawn can be used as thermal binding fibers. Polyethylene or random ethylene-propylene copolymers are used as low melting bonding sites. Before deposition on a moving
belt or screen, the output of a spinneret usually consists of a hundred or more individual filaments which must be attenuated to orient molecular chains within the fibers to increase fiber strength and decrease extensibility.

The web is formed by the pneumatic deposition of the filament bundles onto the moving perforated belt. The web is held by means of a suction current.

For some applications, the filaments are laid down randomly with respect to the direction of the lay down belt. In order to achieve a particular characteristic in the final fabric, the directionality of the splayed filament is controlled by traversing the filament bundles mechanically or aerodynamically as they move toward the collecting belt. In the aerodynamic method, alternating pulses of air are supplied on either side of the filaments as they emerge from the pneumatic jet.

The major elements of the process are:

**Polymer Feed.**
Polymer feedstock in pellet or powder form is conveyed from storage bins or silos to the feeder section of an extruder.

**Extruder.**
The extruder is one of the important elements in all polymer processing. It consists of a heated barrel with a rotating screw inside as shown in figure 4.2.3. Its main function is to melt the polymer pellets or granules and feed them to the next step/element.

![Extruder for polymer melting](image)

**Figure 4.2: Extruder for polymer melting.**

The melting of the pellets in the extruder is due to the heat and friction of the viscous flow and the mechanical action between the screw and the walls of the barrel. There are four different heaters in the extruder, which are set in incremental order. The extruder is divided into three different zones:

i) Feed Zone: In the feed zone the polymer pellets are preheated and pushed to the next zone.

ii) Transition Zone: The transition zone has a decreasing depth channel in order to compress and homogenize the melted polymer.
iii) Metering Zone: This is the last zone in the extruder whose main purpose is to generate maximum pressure in order to pump the molten polymer in the forward direction. At this point the breaker plate controls the pressure generated with a screen pack placed near to the screw discharge. The breaker plate also filters out any impurities such as dirt, foreign particle metal particles and melted polymer lumps.

**Gear pump**

The metering gear pump is a device for uniform melt delivery to the die assembly. It ensures consistent flow of clean polymer mix under process variations in viscosity, pressure, and temperature. The metering pump also provides polymer metering and the required process pressure. The metering pump typically has two intermeshing and counter-rotating toothed gears. The molten polymer from the gear pump goes to the feed distribution system to provide uniform flow to the die nosepiece in the die assembly.

![Gear pump for spunbonding.](figure4.3)

**Fiber Spinning**

The molten polymer mix is pumped through a heated conduit to a resin filter system and then to a distributor section that leads to the spinnerette units.

![Filter system for spunbonding.](figure4.4)
The normal filters are often used for the fabrication of Polyester-Filaments and Micro-Filaments. The XL-Filters have an extremely large pore volume consisting of a large number of woven wire cloth layers with square aperture widths that are arranged over the specific filtration layer. The individual woven wire cloth layers are bonded together as one stable filtration layer via sintering. The edge is formed by a stainless sheet steel ring that, in combination with aluminium flat packings, creates a complete sealing. Depending on the individual usage, the filter layer consists of 15 up to 25 woven wire cloth layers. The pore sizes of the filtration layers range between 20 and 5 micrometers.

The melt passes through the porous filtration layer, arrives at the spinneret nozzle with a high degree of homogeneity and is ideally suited for the spinning process.

The spinnerette usually consists of a perforated plate arranged across the width of the line. The resin is forced through the many small holes in the spinnerette plate to form continuous filaments.

**Quenching / Attenuation Zone**

As the filaments emerge through the spinnerette holes, they are directed downward into quench chambers or chimneys. As the filaments travel through these chambers, cool air is directed across the filament bundle to cool the molten filaments sufficiently to cause solidification. The filaments are then led further downward into a tapered conduit by an airstream. A second stream of high velocity air is directed parallel to the direction of the filaments, causing an acceleration and accompanying attenuation or stretching of the individual filaments. This mechanical stretching results in increased orientation of the polymer chains making up the continuous filament. Such orientation leads to increased filament strength, along with modification of other filament properties, including the filament denier or thickness.

**Web Forming**

The filaments are deposited in a random manner on a moving, porous forming belt. A vacuum under the belt assists in forming the filament web on the forming belt and in removing the air used in the extrusion / orientation operation. In some processes, an electrostatic charge is placed on the filament bundle to ensure spreading and separation of individual filaments. In other processes, deflector plates are used to lay down the filament sheet in a random manner on the forming belt.

**Bonding**

The continuous filament web is delivered to a bonding section, where one of several bonding methods can be used to bond the loose filaments into a strong, integrated fabric.

**Pneumatic gun**

A pneumatic gun uses high-pressure air to move the filaments through a constricted area of lower pressure, but higher velocity as in a venturi tube.
In order for the web to achieve maximum uniformity and cover, individual filaments must be separated before reaching the belt. This is accomplished by inducing an electrostatic charge onto the bundle while under tension and before deposition. The charge may be induced triboelectrically or by applying a high voltage charge. The former is a result of rubbing the filaments against a grounded, conductive surface.

Filaments are also separated by mechanical or aerodynamic forces. The method utilizes a rotating deflector plane to separate the filaments by depositing them in overlapping loops; suction holds the fiber mass in place.
The REICOFIL® spunbonding process is successfully employed to produce Polypropylene, polyethylene, polyester and polyamide nonwovens.

The REICOFIL® spunbonding process has continually been developed since 1986. It is based on the wish to make the process as simple to control as possible and to be energy efficient in comparison to similar processes.

4.2.1. Process components

- Preparation of raw material
- Dosing unit for primary polymer, pigments and additives
- Extruder for melting and conveying the raw materials
- Melt filter
- Spin pump to ensure a constant throughput to the spin unit
- Sheet distributor with spinneret
- Filament cooling
- Filament extension
- Discharge unit (diffuser)
- Web forming machine for discharge and conveyance of the filaments
- Nonwoven bonding, preferable calendering
- Winding

4.2.2. Process description:

Out of the silo the polymer is vacuumfed to dosing station on top of the extruder. Inside the extruder it becomes melted and homogenised. Passing a filter system and a spin pump, the melt is distributed by a coathanger die, feeding the spinneret which forms a curtain of filaments. The filaments are cooled by means of a stream of air in a blowing area, drawn by aerodynamic forces and then transported to the downstream discharge channel. Here the filaments are swirled around and then deposited on the wire mesh belt as a random nonwoven material. This is transferred to the heat bonding calender which by heat and pressure sets the physical properties as tensiles and elongation of the final product. After calendering the material is cooled by a water-cooled pair of rolls and then wound up.

The Reifenhäuser REICOFIL® spunbonding technology convinces by simple handling and low energy consumption (1 - 1.2 kWh/kg) for melting and conveying the raw materials.

4.2.3. Applications

- Hygiene
- Industrial applications
- Dust collectors
- Filtration

4.2.4. Physical properties

- High air permeability
- Thermo-bonded - no chemicals
- Excellent bi-directional and wear properties
- Soft and comfortable
- Grammage between 10 - 100 g/m² (150 g/m²) if possible
- Possible additional nonwoven features:
  - Printing
  - Laminating
  - Electrostatic charging
  - Improved hydrophilic properties through application of tensides
  - By using additives or pigment pastes
  - Dying in every imaginable shade
  - Fire-retardant properties
  - Antistatic properties
  - Increased UV and gamma ray protection

**Figure 4.7: Spunbond line:**

1. Dosing unit
2. Melt preparation
3. Filament production
4. Collection and conveyor unit
5. Nonwoven bonding
6. Nonwoven equipment
7. Winder

Hills company has considerable experience in **bicomponent fibers** for spunbond applications. Fabric widths of over five meters are available. In cooperation with Nordson and Reifenhauser, they offer complete bicomponent spunbond lines.

Bicofil meltblown and spunbond systems deliver excellent performance and flexibility. Bi-component fibers offer improved hand for hygienic and medical products, while maintaining strength and permitting use of recycled polymers for reduced-cost products and splittable fibers for micro-fiber filtration applications. Accommodate sheath/core, side-
by-side, 16-segmented pie and trilobal fiber manufacturing using spinpack configurations. Reduced pack densities for high-denier applications are available.

Protective Outer Layers - A **bi-component spunbond**, using sheath-core technology. The inner core is polypropylene for strength, with a polyethylene wrap for softness. A silver-gray color was selected because of its heat-resistant properties. The fabric is also treated with UV inhibitors for extended outdoor use. Micro-Porous Middle Layer - The barrier layer is breathable film, a proprietary stretch-film technology developed exclusively for Kimberly-Clark. The film is stretched and subjected to a chemical process that creates microscopic holes smaller than droplets of water or dust, yet large enough to allow moisture vapor to escape. Soft, Paint-Protecting Inner Layer - A bi-component fabric made with polyethylene and nylon. This combination results in an exceptionally high strength-to-weight ratio, with the "soft touch" necessary for today's water-based paint finishes.

| Construction principle of staple fiber and conventional spunbond nonwoven fabrics |
|-----------------|----------------|----------------|
| Fiber            | Staple fiber nw fabrics | Spunbond nw fabrics |
| Fiber length     | 38 — 90 mm          | Continuous (endless) |
| Shape of fiber along its length | Crimped          | Not crimped |
| Fiber orientation in the fabric at high speed manufacturing | anisotropic | isotropic (random) |
| Range of processable fiber fineness | 0,8 — 50 dtex | 0,5 — 10 dtex |
| Fiber forming polymer | Whole range available | Restricted on melt spinnability |

| Fabric characteristics staple fiber versus spunbond nw fabrics |
|-----------------|----------------|----------------|
| Fabric characteristics | Staple fiber nw fabrics | Spunbond nw fabrics |
| Mechanical strengths over all | low | high |
| in md (machine direction) much higher than in cd (cross direction) | no big difference between cd and md |
| Elongation | in cd much higher than in md | no big difference between cd and md |
| Softness | high | low |
| Stiffness | low | high |
| Drapability | high | low |
| Loftiness | high | low |
| Resiliency | high | low |
| Textile properties over all | high | low |
Summerized over all conventional spunbond nonwoven fabrics provide much higher mechanical strengths in md and cd than carded nonwoven fabrics but because of the non crimped fibers all characteristics derived from such as softness, drapability, loftiness and the like are uncomparably worse than with carded nonwoven fabrics. Expressed somewhat simplified: the non-textile characteristics of conventional spunbonds has been so unfavorable that huge areas of application such as garment industry or upper material for shoes and luggage could not be covered by them.

Figure 4.8: SB side-by-side -60PET_40PA66

Figure 4.9: SB 16 segment pie -70PET_30PA66

In-line-production is illustrated schematically in figure 4.10, starting from polymer granule and ending with the ultrafine microfiber spunbond fabric. Two different polymers are transported by extruders to the spinneret, leaving it as bicomponental endless filaments, which
are quenched and stretched by air streams with a very high speed up to sonic velocity. The stretched filaments are finally laid down onto a moving belt to form a nonwoven fabric of uniform structure. As demonstrated later in more detail the fiber distribution is more or less an isotropical one. Mechanical strengths are practically the same in machine and cross direction which might beneficial for most part of applications.

**Figure 4.10: Scheme of industrial omega-line.**

### 4.3. Melt-blowing process (MB)

Melt blowing is a process for producing fibrous webs directly from polymers using high-velocity air to attenuate the filaments. MB microfibers generally have diameters in the range of 2 to 4 µm, although they may be as small as 0.1 µm and as large as 10 to 15 µm. Differences between MB nonwoven fabrics and other nonwoven fabrics, such as degree of softness, cover or opacity, and porosity can generally be traced to differences in filament size. The Melt blowing is process in which high-velocity air blows a molten thermoplastic resin from an extruder die tip onto a conveyor or takeup screen to form a fine fiberous and self-bonding web.

**Figure 4.11: Melt blowing processing.**

The die assembly is the most important element of the melt blown process. It has three distinct components: polymer-feed distribution, die nosepiece, and air manifolds.

#### 4.3.1. Essential features of the process:

- Resin storage and resin preparation
- Metering unit for main polymer, pigments
Approx. 40% of the MeltBlown material is manufactured in a stand-alone process. The remaining meltblown materials are combined with spunbonded fabrics or laminates to form other materials. Combinations with spunbonded fabrics are primarily used to make nonwoven materials with barrier properties. Another variation is the combination of MeltBlown with cellulose or an absorbent powder, to produce a soft, strong but still absorbent material, which can retain absorbed liquid whilst still keeping its strength.

**Polymer** The MeltBlown process allows the use of various different polymers: polypropylene MFI 400 - 1500, polyethylene MFI 20 - 200, polyester iV 0.53 - 0.64, polyamide, polyurethane, polyphenylene sulphide. All of the polymers used during MeltBlown production must have a low viscosity. This results in a relatively high melt temperature (compared to other production processes). The melt temperature can be adjusted during production by means of electrical heating systems in the extrusion section.
hydrophobic / oleophilic
- Excellent wick properties / liquid retention
- High filtration efficiency
- Thermal insulation
- Elasticity
- Preferred grammage spectrum 5 - 500 g/m²
- Preferred filament diameter 1 - 2 µm
- Porosity
- Surface energies
- Colours can be used
- .. and many others

Feed Distribution
The feed distribution in a melt-blown die is more critical than in a film or sheeting die for two reasons. First, the melt-blown die usually has no mechanical adjustments to compensate for variations in polymer flow across the die width. Second, the process is often operated in a temperature range where thermal breakdown of polymers proceeds rapidly. The feed distribution is usually designed in such a way that the polymer distribution is less dependent on the shear properties of the polymer. This feature allows the melt blowing of widely different polymeric materials with one distribution system. The feed distribution balances both the flow and the residence time across the width of the die.

Die Nosepiece
From the feed distribution channel the polymer melt goes directly to the die nosepiece. The die nosepiece is a wide, hollow, and tapered piece of metal having several hundred orifices or holes across the width. The polymer melt is extruded from these holes to form filament strands which are subsequently attenuated by hot air to form fine fibers. A typical die nosepiece has approximately 0.4-mm diameter orifices spaced at 1 to 4 per millimeters (25 to 100 per inch).

There are two types of die nosepiece used: capillary type and drilled hole type. For the capillary type, the individual orifices are actually slots that are milled into a flat surface and
then matched with identical slots milled into a mating surface. The two halves are then matched and carefully aligned to form a row of openings or holes. By using the capillary type, the problems associated with precise drilling of very small holes are avoided. In addition, the capillary tubes can be precisely aligned so that the holes follow a straight line accurately. The drilled-hole type has very small holes drilled by mechanical drilling or electric discharge matching (EDM) in a single block of metal.

![Diagram of die nosepiece showing capillary and drilled hole types](image)

*Figure 4.13: Two types of die nosepiece: capillary and drilled hole.*

**Air manifolds**

The air manifolds supply the high velocity hot air through the slots on the top and bottom sides of the die nosepiece. The high velocity air is generated using an air compressor. The compressed air is passed through a heat exchange unit such as an electrical or gas heated furnace, to heat the air to desired processing temperatures. Typical air temperatures range from 230°C to 360°C at velocities of 0.5 to 0.8 the speed of sound.

As soon as the molten polymer is extruded from the die holes, high velocity hot air streams attenuate the polymer streams to form microfibers. As the hot air stream containing the microfibers progresses toward the collector screen, it draws in a large amount of surrounding air that cools and solidifies the fibers.

The solidified fibers subsequently get laid randomly onto the collecting screen, forming a self-bonded nonwoven web. The fibers are generally laid randomly because of the turbulence in the air stream, but there is a small bias in the machine direction due to some directionality imparted by the moving collector. The collector speed and the collector distance from the die nosepiece can be varied to produce a variety of melt-blown webs. Usually, a vacuum is applied to the inside of the collector screen to withdraw the hot air and enhance the fiber laying process.

**Machine variables**

Machine variables, also called operational variables, are related to the machine and can be changed while the equipment is being operated. These variables include air temperature, polymer/die temperature, die to collector distance, collector speed, polymer throughput and air throughput. All of these affect the final properties of the nonwoven web.

i) Polymer Throughput and Air Flow: both polymer throughput and air flow rate control the final fiber diameter, fiber entanglement, basis weight and the attenuating zone.
ii) Polymer/Die and Air Temperature: These variables combined with air flow rate affect the uniformity, shot formation (large globules of nonfibrous polymer larger in diameter than fibers in webs), rope and fly formation, fabric appearance and feel (soft or stiff).

iii) Die to Collector Distance: This affects the openness of the fabric, thermal bonding among the fibers and basis weight.

**Off-line variables**

Off-line variables are fixed during a process run and can only be changed when the machine is not in operation. These variables are air gap, air angle, die setback, and die hole size.

i) Die Hole Size: Die hole size along with die set back affects the fiber size.

ii) Air Gap: It affects the degree of fiber breakage by controlling the air exit pressure.

iii) Air Angle: It controls the nature of air flow, i.e. as the air angle approaches 90° it results in a high degree of fiber separation or turbulence that leads to random fiber distribution. At an angle of 30°, roped or parallel fibers deposited as loosely coiled bundles of fibers are generated. This structure is undesirable. At angles greater than 30°, attenuation as well as breakage of fibers occurs.

4.3.4. Stand-alone type

The characteristic feature of the stand-alone system is the collector, which can be adjusted in height and angle. This patented design allows precise control of the MeltBlown deposition.

![Figure 4.14: Two types of collectors: stand-alone system and inline type.](image)

4.3.5. Inline type

Since the common collectors of composite-lines have static height, the adjustment of the die-distance to collector belt (DCD) is done by vertical movement of the entire operating platform.

**Properties of melt-blown**

Melt-blown webs usually have a wide range of product characteristics. The main characteristics and properties of melt-blown webs are as follows:
- Random fiber orientation.
- Lower to moderate web strength, deriving strength from mechanical entanglement and frictional forces.
- Generally high opacity (having a high cover factor).
- Fiber diameter ranges from 0.5 to 30 µm, but typically from 2-7 µm.
- Basis weight ranges from 8-350 g/m², but typically 20-200 g/m².
- Microfibers provide a high surface area for good insulation and filtration characteristics.
- Fibers have a smooth surface texture and are circular in cross-section.
- Most melt-blown webs are layered or shingled in structure, the number of layers increases with basis weight.

The fiber length in a melt-blown web is variable; it can be produced in the range from a few millimeters to several hundred centimeters in length and usually exists over a broad range. The fiber cross-section is also variable, ranging from circular to a flat configuration and other variations.

**Type of polymer**

The type of polymer or resin used will define the elasticity, softness, wetability, dyeability, chemical resistance and other related properties of formed fibers. One of the advantages of melt-blown technology is to handle many different polymers as well as mixture of polymers. Some polymers, which can be melt-blown, are listed below. However, the list is not complete.

- Polypropylene is easy to process and makes good web.
- Polyethylene is more difficult to melt-blow into fine fibrous webs than is polypropylene. Polyethylene is difficult to draw because of its melt elasticity.
- PBT (poly-butylene terephalate) processes easily and produces very soft, fine-fibered webs.
- Nylon 6 is easy to process and makes good webs.
- Nylon 11 melt-blows well into webs that have very unusual feel like leather.
- Polycarbonate produces very soft-fiber webs.
- Poly (4-methyl pentene-1) blows well and produces very fluffy soft webs.
- Polystyrene produces an extremely soft, fluffy material with essentially no shot defects.

The most widely used polymer that has a high MFR is polypropylene. Polypropylene with its low viscosity has a low melting point and is easy to draw into fibers. It comprises 70-80% of the total North American production.

The feasibility of MB original and recycled PET has also been studied. PET webs have a strong tendency to shrink, depending on the airflow rate used. PET webs produced at high airflow rate shrink more than those produced at low airflow rate because of their higher level of molecular orientation. Heat-setting of melt-blown PET webs or, alternatively, the use of PBT was suggested as a possible means of producing thermally stable melt-blown PET nonwovens.

**Bicomponent melt blown**

Hills company has successfully designed and put into commercial application bicomponent melt blown systems that produce sheath/core, side-by-side, tipped trilobal and tipped cross fibers with approximately 2 micron diameters. These bicomponent systems operate on conventional meltblown spin hole densities. In addition, Hills has developed melt
blown dies with 100 holes per inch that operate with homopolymer at throughputs up to 0.5 grams per hole per minute.

In combination with the patented Hills-meltdistribution Reifenhäuser REICOFIL delivers Bico-Nonwovenlines up to 4.2m working width.

The polymer flow is given by the follow:

$$\frac{dm}{dt} = \varphi \, \frac{\pi \, d_0^2}{4} \, v_0 = \varphi \, \frac{\pi \, d^2}{4} \, v_f$$

where
- $\varphi$ is density of polymer
- $d_0$ is diameter of spinning nozzle
- $v_0$ polymer flow rate into the nozzle
- $d$ final diameter of fiber
- $v_f$ final (maximal) fiber rate

Figure 4.15: Bicomponent melt blown system.
4.4. Flash spinning

Flash-spinning is a deviation from the conventional melt spinning process and is a process created by DuPont company. In flash-spinning, pure solvent droplets and highly saturated polymer/solvent mixtures are decompressed through a spin orifice. As the pressurized solution is allowed to expand rapidly through the orifice, the solvent is instantaneously "flashed off," leaving behind a three-dimensional film-fibril network.

![Flash spinning schematic](image)

The micro-denier fibers that are produced via this process are interconnected in a continuous network and collected on a moving belt. Then, the sheet is subjected to either full-surface thermal bonding, which creates a stiff, paper-like sheet, or point bonding, followed by in-line softening which creates a drapeable, fabric-like sheet. No binders are used. As a result of this unique process—and its composition of 100% high-density polyethylene—the finished product offers a high surface area and enhanced filtration efficiency, as well as good sheet tensile and high tear strength.

**Construction**

One of the most popular and widely known applications of Tyvek® is in the construction industry, where it is used to increase air and water resistance, helping to lower heating and cooling costs in buildings and providing better protection against water and moisture intrusion. The unique qualities of Tyvek® help stop air flow through wall cavities; help hold out bulk water and wind-driven rain; and allow moisture vapor to escape from inside walls. The result is a more comfortable, energy-efficient building with far fewer chances for damage from degradation effects.
Medical Packaging

Tyvek® is used in virtually every form of sterile medical packaging. That's because Tyvek® delivers an optimum balance of bacteria penetration resistance, tear strength, puncture resistance and clean peel, as well as compatibility with existing and emerging sterilization methods.

Protective Apparel

Garments made of Tyvek® are either used for hazardous environments or for general, non-hazardous, industrial use. Examples of uses for hazardous environments include protection against water-based acids, bases, salts and splashes of certain liquids, such as pesticides and herbicides.

Envelopes

The unique composition of Tyvek® results in virtually the strongest envelope available – offering superior protection from punctures, tears and moisture. Remarkably light, Tyvek® envelopes can help to save on mailing costs.

Graphics

Among the first graphic products manufactured from hard-structure Tyvek® were outdoor advertising posters and banners; labels; tags; and schoolbook covers – applications that benefit from its water, abrasion and tear resistance. Today, many more graphics uses have been found for Tyvek®, such as highly durable maps and guidebooks; chemical container labels; workshop manuals; race numbers for marathon runners; and frozen food labels.

Covers

Because Tyvek® is water resistant, yet breathable, it is ideal for car, boat and camper covers. The unique nonwoven structure of Tyvek® protects against acid rain and salt spray by holding out more water than cotton, polyester or cotton/polyester covers; however, because it is breathable, it also allows trapped moisture to escape, helping to prevent rot and mildew.

4.5. Spunbond and melt blown modification

SMS

The operation begins by spinning continuous filaments from the spunbond die of station one. The filaments pass through the quenching zone, which cools and prevents them from sticking together. The quenched filaments pass through a stretching zone where discharged air further draws down and attenuates the filaments. Filaments are randomly deposited on the conveyor. Air passes through the conveyor and is withdrawn by the vacuum system. The first layer is conveyed under the spinning assembly in station two where micro-sized fibers are blown on top of the first layer, forming a meltblown layer on the spunbond. Average fiber diameter ranges from 0.5 to 15 microns. A fiber diameter of 1 to 10 microns is considered good, while 2 to 6 microns is excellent.
The two-layer laminate is conveyed under station three where a layer of spunbond filaments is deposited on the meltblown layer, completing the SMS structure. The three-layer composite may then pass though a calender or other device to bond the layers together in the conventional manner.

Typical products of spunbond and meltblown technologies are:
### Product Fabric

**Disposable Diaper, Incontinence**
- Largest single market segment in nonwovens for cloth-like backsheet, leg cuff and cover stock

**Durable Papers**
- Almost exclusively Tyvek® polyethylene spunbond fabric (Tyvek is a registered trademark of E.I. DuPont de Nemours & Co.)

**Disposable, Protective Apparel**
- Dominated by Tyvek polyethylene spunbond fabric, although growing use of polypropylene spunbond and composite materials

**Bedding, Pillows, Furnishings**
- Competitive market segment using polypropylene and polyester spunbonds

**Geotextiles**
- Heavyweight polypropylene and polyester spunbonds, and needlepunch polypropylene and woven fabrics

**Furniture**
- Polypropylene spunbond fabric, polypropylene needlepunch and polyester spunbond fabric

**Filtration**
- Spunbond and meltblown fabric for liquid and air filtration

**Automotive, Carpet, Trim**
- Heavyweight polyester spunbond fabrics

**Carpet Underlayment**
- Carpet backings consisting of PET, polyamide and polypropylene spunbond fabrics

**Medical Products**
- Spunbond and spunbond/meltblown composite fabrics

**Roofing**
- Typically polyester spunbonds

Air laid sorbents are manufactured using a state-of-the-art process that produces a 100% polypropylene sorbent. The polypropylene fibers are ultrasonically bonded between two layers of spunbond fabric.

Sonic bonded low-lint absorbents are manufactured by ultrasonically bonding two layers of melt-blown polypropylene. This construction gives sonic bonded products greater strength than regular melt-blown sorbents, and also provides low-lint properties.

Fine fiber sorbents consist of two layers of fine fiber polypropylene ultrasonically bonded around a high-loft melt-blown core. These low-lint pads and rolls have the highest absorption rates of all our products.

4.5.1. Primary process characteristics:

- Modular structure of the spunbonding and melt blown components
- Common operating console for all spinning stations
- Common high-speed spinning belt for all spinning stations.
- High-speed winding system with downstream slitter/rewinder

Approx. 40% of all melt blown fabric is manufactured as pure melt blown fabric, the rest is used in composites with spunbonded fabric or in laminates with film.
4.5.2. Applications

- Barrier products
- Diaper edges
- Filtration
- Covers for superabsorbents
- Medical applications (for example surgery covers)

4.5.3. Physical properties

- Thermo-bonded
- High resistance against water column
- Thermal insulator
- Preferred grammage range 10 - 60 g/m²
- Dyable

4.5.4. Oil control products

**FineFiber** technology produces densely-woven, small-diameter strands of fiber to increase surface area for fast absorption and firmer grip. Add 3-ply construction for extra durability and you have a mat that you can walk on safely and is virtually indestructible to foot traffic.

**AirLaid** technology produces a resilient bounce-back polypropylene fiber that creates uniform pockets of air space that sorb and hold liquids. Insert AirLaid polypropylene between two layers of tough spunbond and bond ultrasonically for added strength. Now you have an ideal mat for wrapping around pipes or fitting into tight spots to help maintain a cleaner, safer workplace.

**MultiLaminate** technology produces a super-strong, heavy-weight mat for rugged applications. Outer spunbond layers constructed of continuous strands of interwoven polypropylene fibers provide toughness while the MeltBlown inner layer draws and traps ugly grime inside. Resistant to tears and abrasions, this mat is perfect for lining tool cribs and placing under jagged parts and heavy equipment.

**SonicBonded** technology produces a high-loft mat for faster, greater absorbency. Fuse the layers together with ultrasonic weld points and you’ve got a mat that sucks up to 57.5
gallons per roll and keeps its shape even when fully saturated. In other words, it won’t fall apart! Great for overspray areas and indoor spills where clean, dry floors are important for safety.

4.6. Electrostatic spinning

In the electrospinning process a high voltage is used to create an electrically charged jet of polymer solution or melt, which dries or solidifies to leave a polymer fiber. One electrode is placed into the spinning solution/melt and the other attached to a collector. Electric field is subjected to the end of a capillary tube that contains the polymer fluid held by its surface tension. This induces a charge on the surface of the liquid. Mutual charge repulsion causes a force directly opposite to the surface tension. As the intensity of the electric field is increased, the hemispherical surface of the fluid at the tip of the capillary tube elongates to form a conical shape known as the Taylor cone. With increasing field, a critical value is attained when the repulsive electrostatic force overcomes the surface tension and a charged jet of fluid is ejected from the tip of the Taylor cone. The discharged polymer solution jet undergoes a whipping process wherein the solvent evaporates, leaving behind a charged polymer fiber, which lays itself randomly on a grounded collecting metal screen. In the case of the melt the discharged jet solidifies when it travels in the air and is collected on the grounded metal screen.

The above description of the process suggests that the following parameters affect the process:

- Molecular Weight, Molecular-Weight Distribution and Architecture (branched, linear etc.) of the polymer
- Solution properties (viscosity, conductivity & and surface tension
- Electric potential, Flow rate & Concentration
- Distance between the capillary and collection screen
- Ambient parameters (temperature, humidity and air velocity in the chamber)
- Motion of target screen

An important characteristic of electrospinning is the ability to make fibers with diameters in the range of nanometers to a few microns. Consequently these fibers have a large surface area per unit mass so that nanowoven fabrics of these nanofibers collected on a screen can be used for example, for filtration of submicron particles in separation industries and biomedical applications, such as wound dressing in medical industry, tissue engineering scaffolds and artificial blood vessels. The use of electrospun fibers at critical places in advanced composites to improve crack resistance is also promising.

A schematic diagram of electrospinning is as shown in Figure 4.19. The process makes use of electrostatic and mechanical force to spin fibers from the tip of a fine orifice or spinneret. The spinneret is maintained at positive or negative charge by a DC power supply. When the electrostatic repelling force overcomes the surface tension force of the polymer
solution, the liquid spills out of the spinneret and forms an extremely fine continuous filament. It has the misleading appearance of forming multiple filaments from one spinneret nozzle, but current theory is that the filaments do not split.

These filaments are collected onto a rotating or stationary collector with an electrode beneath of the opposite charge to that of the spinneret where they accumulate and bond together to form nanofiber fabric. The distance between the spinneret nozzle and the collector generally varies from 15 –30 cm. The process can be carried out at room temperature unless heat is required to keep the polymer in liquid state. The final fiber properties depend on polymer type and operating conditions. Fiber fineness can be generally regulated from ten to a thousand nanometers in diameter.

![Figure 4.19: A schematic diagram of electrospinning](image)

The polymer is usually dissolved in suitable solvent and spun from solution. Nanofibers in the range of 10-to 2000 nm diameter can be achieved by choosing the appropriate polymer solvent system. Table 1 gives list of some of polymer solvent systems used in electrospinning.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Solvents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon 6 and nylon 66</td>
<td>Formic Acid</td>
</tr>
<tr>
<td>Polyacrylonitrile</td>
<td>Dimethyl formaldehyde</td>
</tr>
<tr>
<td>PET</td>
<td>Trifluoroacetic acid/Dimethyl chloride</td>
</tr>
</tbody>
</table>
4.6.1. **Device for electrostatic spinning**

This technology consists depositing the polymer onto a conveyer of heated wires giving a high voltage potential. The polymer covering the wires, pass over the second conveyer with substrate onto witch the fibers are created.

![Electrostatic spinning device](image)

*Figure 4.20: Electrostatic spinning device.*

4.7 **Solution spinning**

A device for nanofibres production from a polymer solution uses electrostatic spinning in an electric field created by a potential difference between a charged electrode and a counter electrode consisting of a container (4) at least partly filled with a polymer solution (1) in which is by a part of its circumference immersed pivoted cylinder (2), which is by a well-known not represented method connected to a source of DC voltage and which forms a charged electrode. Against a free part of the circumference of the charged electrode (2) is a
counter electrode (3) with a different potential situated, which is usually connected to earth (grounded), as described in Fig. 4.21, or it is by a well-known not represented method connected to a source of DC voltage of a different polarity.

Figure 4.21: The polymer solution (1) is for spinning supplied into the electric field using the surface of the rotating charged electrode (2), while on a part of the circumference of the charged electrode near to the counter electrode (3) is a spinning surface created, by which is a high spinning capacity reached. Further the invention relates to a device for carrying out the method, where the charged electrode is pivoted and by its (bottom) part of its circumference it is immersed in the polymer solution, while against the free part of the circumference of the charged electrode is positioned the counter electrode.

By rotating the charged electrode, where its part of its circumference is immersed in the polymer solution, is the polymer solution drawn by the circumference of the charged electrode from the container into the space between the charged electrode and the counter electrode, where an electric field is formed. Here on the surface of the charged electrode are from the polymer solution formed Taylor cones of a high stability and they present places of primary formation of the nanofibres (8). The formed nanofibres are by the effects of electric field drift away to the counter electrode and consequently they are deposited on the surface of the backing fabric presenting plane supporting material (5) of the nanofibres into a layer, which thickness is controlled using the velocity of the unreeling device (6) and the reeling device (7). The drift of the nanofibres away of the charged electrode to the counter electrode is promoted by streaming of air sucked from the outer space into the vacuum chamber (9) and passing along the polymer solution container and the charged electrode and passing through the backing fabric presenting plane supporting material of the nanofibres and the counter electrode.

A method and a device according to the invention are applicable for production of layers of nanofibres in diameters from 50 to 200 nanometers.
These layers can be used for filtration, as battery separators, for production of special composites, for construction of sensors with extremely low time constant, for production of protective clothes, in medicine and other fields.