5.2 CA Filter Tow for Cigarette Filters

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Summary: Important steps in the process of the transformation of cellulose acetate flakes into Filter Tow and then into filters are explained: dissolving of cellulose acetate in acetone, extrusion of spin dope through spinnerets, crimping of tow band, drying and baling, rod making. Quality parameters of Filter Tow and filters are summarized as well as. The effect of selective filtration of cellulose acetate cigarette filters.

5.2.1 Summary of Usage of CA Filter Tow and Market Evolution

Since its introduction into the market in 1952 [1], CA Filter Tow, which is made from crimped endless CA filaments, has seen a tremendous growth in the cigarette market. In 2003, the volume of manufactured Filter Tow reached a new record of more than 600 000 metric tons (see figure 1). The major reasons for this growth of CA in cigarette filters are

- the growth in the percentage of cigarettes using filters
- the substitution of other filtration materials like paper, cotton and polypropylene
- the overall growth of worldwide cigarette consumption, mainly due to the growing population.

In 1955, intensive and quite successful marketing for filter tipped cigarettes started in the USA (see figure 2). The European market followed with a classical five years delay. After the opening of the Chinese market in 1990, cellulose acetate filters were successfully introduced in the biggest cigarette market in the world.

This successful introduction of cellulose acetate filters in more than 90% of the consumed cigarettes in the world is due to the following advantages:

- cellulose acetate material is non toxic, tasteless and odorless,
- cellulose acetate is stable to storage under varying conditions of humidity and temperature,

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- cellulose acetate allows the production of filters with a uniform, firm structure and a pressure drop within very closely prescribed limits,
- because it is a continuous tow band it can be converted into filters at rapid speeds and also into individually designed filters,
- cellulose acetate filters can be hardened with a plasticizer which neither adheres to the equipment which it passes nor requires a solvent removal during the formation of the filter rod,
- Filter Tow has the unique material inherent advantage of the selective removal of phenols, nitrosamines, quinolines and other undesired smoke components,
- CA has a preferred "taste signature"
- Cellulose is a biodegradable substance

The intention of this paper is to give a short overview on how cellulose acetate is manufactured, what the characteristics of a Filter Tow are, how Filter Tow is transformed into filters and what the main features of cigarette filters are.

5.2.2 Manufacturing of Filter Tow

Dope preparation

To make the spinning solution, ("dope") acetate flakes, acetone and some water are mixed together intensively in a mixer. Acetone is an ideal solvent for cellulose acetate; moreover, it is safe from a health point of view. A small amount of titanium dioxide is added as a white pigment for declustering the filaments. To ensure a stable spinning process, it is important that the initial substances are always of the same consistent quality and the composition of the spinning solution does not fluctuate. Furthermore, the spinning solution should be freed of as many particles, (e.g., pieces of bark from the cellulose manufacturing process, cellulose fibre remnants and larger titaniumdioxide agglomerates) as possible. To achieve this, the spinning solution is filtered in filter presses with very large surface areas.

This ensures that the fine spinning jets do not get blocked.

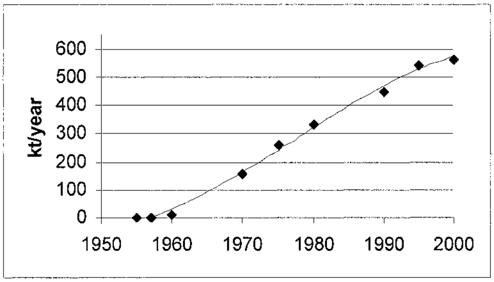

Fig. 1: Market development of Filter Tow [2,3]

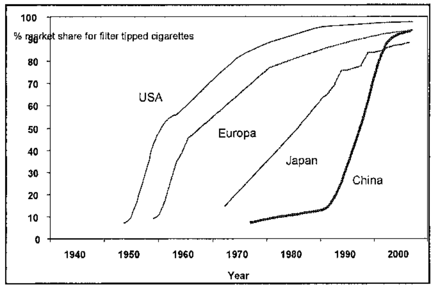

Fig. 2: Development of the market share of CA filter – tipped cigarettes

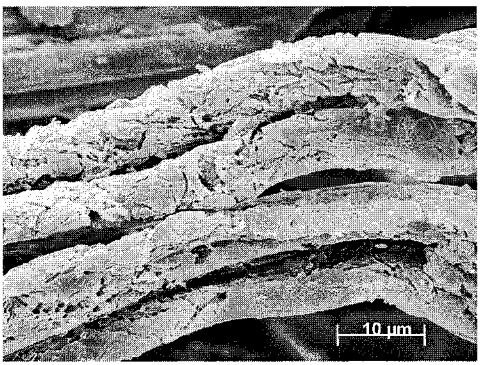

Fig. 3a: Scanning electron micrograph of a biologically degraded Cellulose Acetate Filament

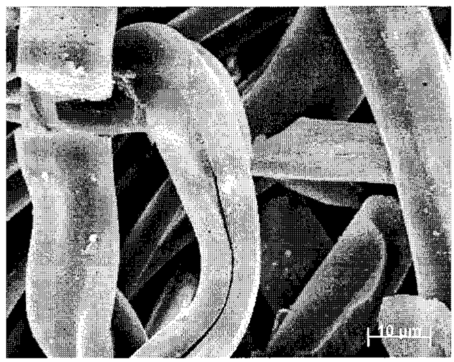

Fig. 3b: Scanning electron micrograph of a Cellulose Acetate Filament after irradiation: tiny holes in the surface are caused by photo oxidation around the TiO2-pigments

The Spinning Machine

The spinning machine for Filter Tow comprises of three parts:

– the spinning head, in which the spinning solution is maintained at the exact temperature and is fed into the spinning jets by spinning pumps. The spinning jets are the heart of the spinning machine

- a series of spinning cells, in which the actual thread formation takes place below the spinning jets and where most of the acetone is removed by evaporation with the help of air.

– tow band guide, in which the elementary threads from the individual cells are united to form a cable.

After the spinning solution has come out of the spinning jets and the acetone evaporates, the newly born filament solidifies and becomes thinner. For a typical filter tow more than 10.000 filaments are spun from many jets in a series of spinning cabinets and united to form a band which is subsequently crimped.

Recovery of Acetone

Since more than 70% of the spinning solution comprises of acetone, the acetate spinning process can only be profitable and environmentally friendly when practically all the acetone is recovered. To achieve this, the suction-extracted air/acetone mixture is finally separated in a distillation column.

Crimping

The crimping process serves to emboss a crimping structure onto each filament in the filter tow . In the crimper, the uncrimped tow band is pressed via two feed rolls into a stuffer box. This is constructed so that over a prolonged period a very consistent, fine and regular crimping is achieved along the entire tow width - as is required by the customer for a consistent filter rod production.

Drying, Storage, Pressing, Packaging

The fresh crimp structure is fixed as it passes through a drier and the filter tow is brought to a consistent final humidity. The filter tow is then laid into filling boxes several metres tall in regular patterns. This loosely packed tow layer is then compressed by bale presses into filter tow bales and packed for dispatch.

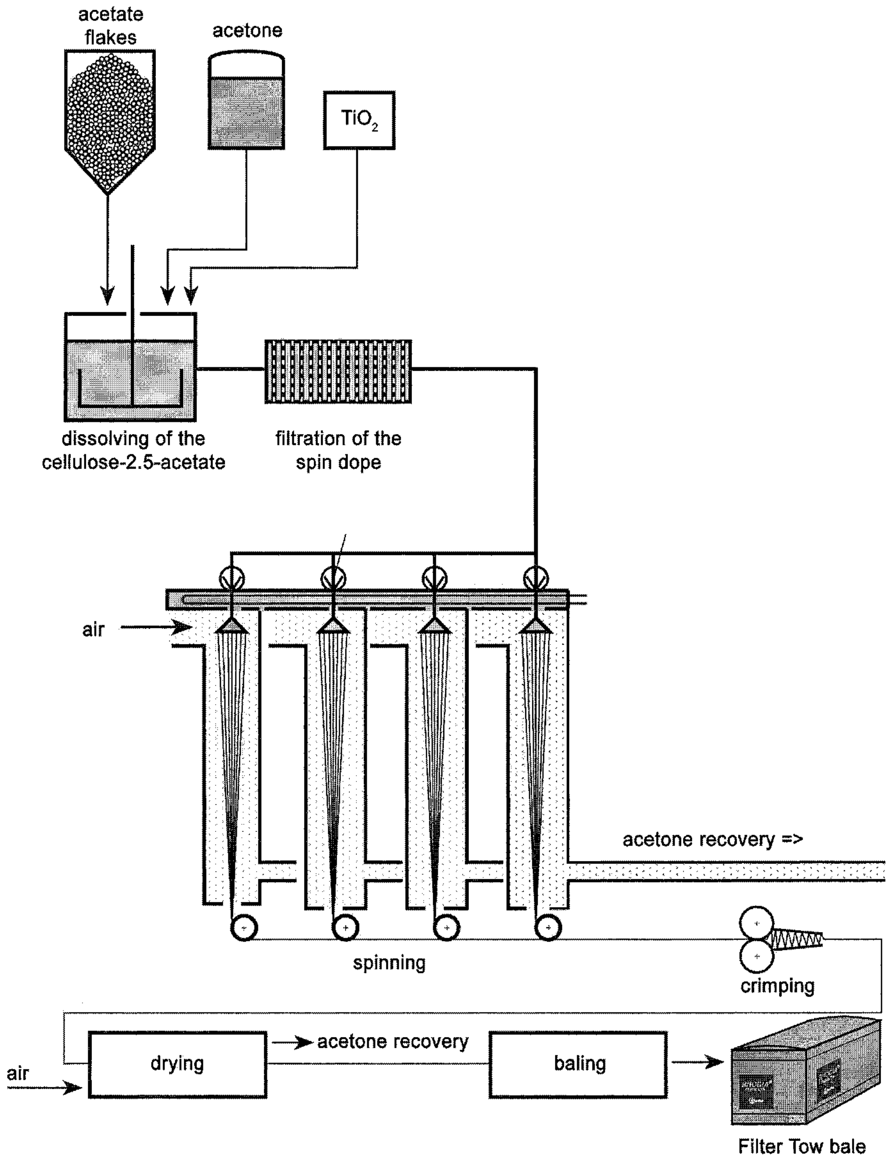

Fig. 4: Overview of a spinning machine

The Birth of a Filament

How a triangle becomes a "Mercedes Star"

In the spinning solution the CA molecules are in the form of clusters and are "completely soaked" with acetone. Above a concentration of approximatively 24% they are strongly hooked into and coiled around each other, so that they can practically no longer shift against adjacent molecules. If the highly viscous acetate spinning solution is now pressed through the holes in the spinning jets, the polymeric clusters undergo elastic deformation and are orientated in the direction of spinning. In doing this, they absorb a large part of the energy brought into the system by the spinning pumps. When coming out of the spinning jet the polymeric clusters relax again and the solution stream expands up to a diameter of aprox. twice that of the diameter of the jet bore. The elastic energy is converted into heat. From the moment the solution is extruded, the acetone solvent evaporates and the polymeric solution concentrates and cools down. Both effects cause a rapid solidification of the filament surface.

Since the draw down speed is usually higher than the extrusion speed from the spinnerette holes, the plastic filament is stretched, orientating the polymeric molecule clusters in the direction of the fibre [4].

To gain a high surface area of the Filter Tow, Y-shaped cross-sections of the filaments are produced. Interestingly, these are generated from spinnerets holes with triangular cross-sections. During the evaporation of the acetone, the skin of the filament solidifies, followed by further acetone diffusing from inside of the filament through this skin to the outside. The edges of this triangle solidify first and then the surfaces shrink during the drying process toward the centre of the triangle. Figure 6 on the right side shows the cross-sections of acetate filaments within the corresponding geometric shapes of the nozzle. By 1970 the utilisation of I-shaped (dog-bone) Filter Tow was stopped.

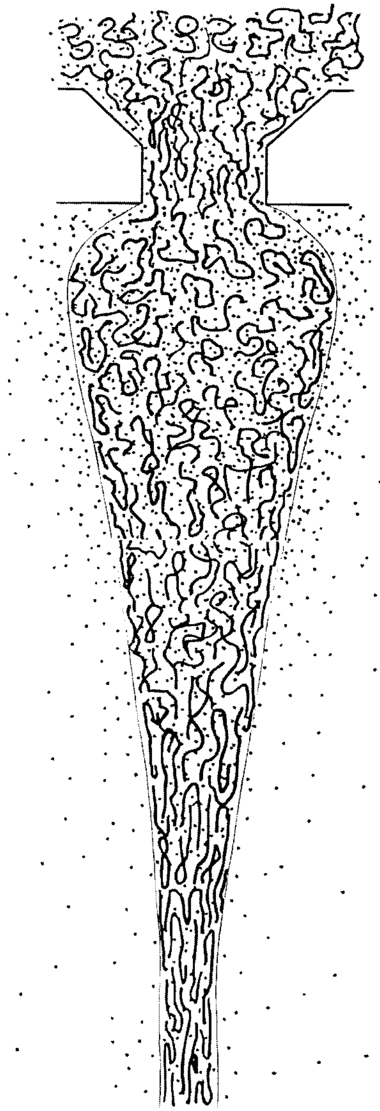

Fig. 5: Filament formation after the jet: elastic expansion, acetone evaporation and draw down effects make the filaments tall.

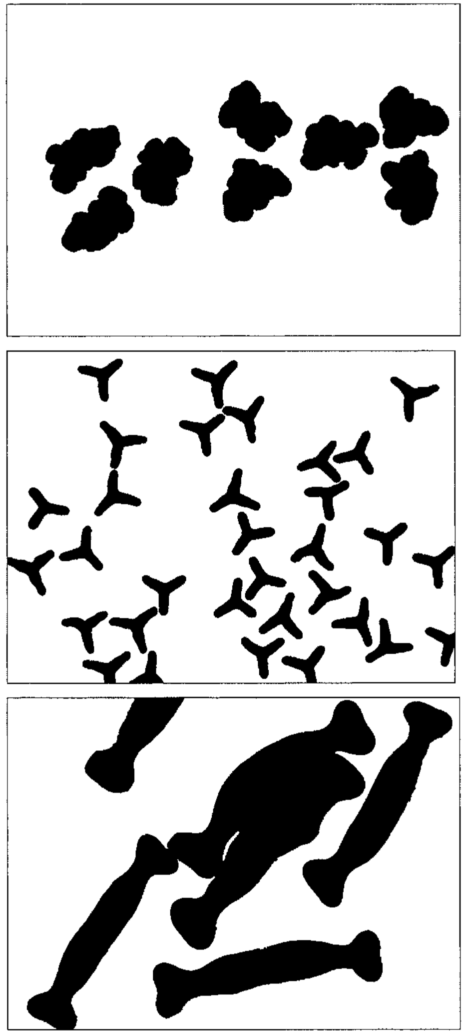

Fig. 6: Micrographs of CA filaments spun from round; triangular and rectangular shaped spinneret holes.

5.2.2.1 The Crimping Process

Crimping means the zig-zag-shaped deformation of the originally straight filaments. For Filter Tow crimping is one of the most important criteria determining quality. Crimping determines, on the one hand, the elastic behaviour of the tow in the processing within the filter rod machine and, on the other hand, the appropriate matrix structure of the finished cigarette filter.

The following criteria are those which determine the quality of the Filter Tow:

Crimp-Index (Number of crimps per cm)

The higher the number of small crimps present in the filament, the higher its elasticity and spring-back resilience is. The higher the number of points of intersection, the higher the air resistance and the variations generated later in the filters.

Consistency of the Crimping

The consistency of the crimping is decisive for the consistency of the cigarette filters later produced.

How does the Stuffer Box Crimping Process work?

A so-called stuffer box crimping process is used to crimp acetate Filter Tow.

A crimping machine basically comprises of a stuffer box, in which the tow band of over 10,000 filaments (= cable) is continually introduced via two feed rollers. At its rear end, the stuffer box has a flap which is pressed under constant pressure against the acetate cable as it fills the chamber. The feed rolls thus press the cable against a plug, the cable first of all being compressed like an accordion into a finely crimped form. These primary crimped packets are then compressed like an accordion into secondary crimped layers and, finally, into tertiary crimped layers. It goes without saying that at equilibrium exactly the same amount of crimped acetate cable leaves the chamber as uncrimped cable is fed in.

The fineness of the crimping in this process is mainly determined by the elasticity of the filaments, the applied compression and the overall geometry of the crimping machine [5].

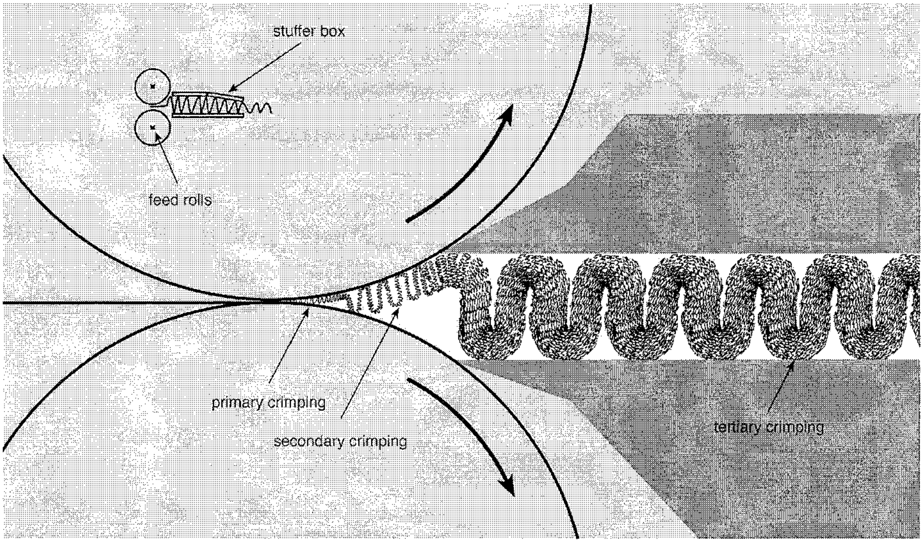

Fig. 7: The crimping process

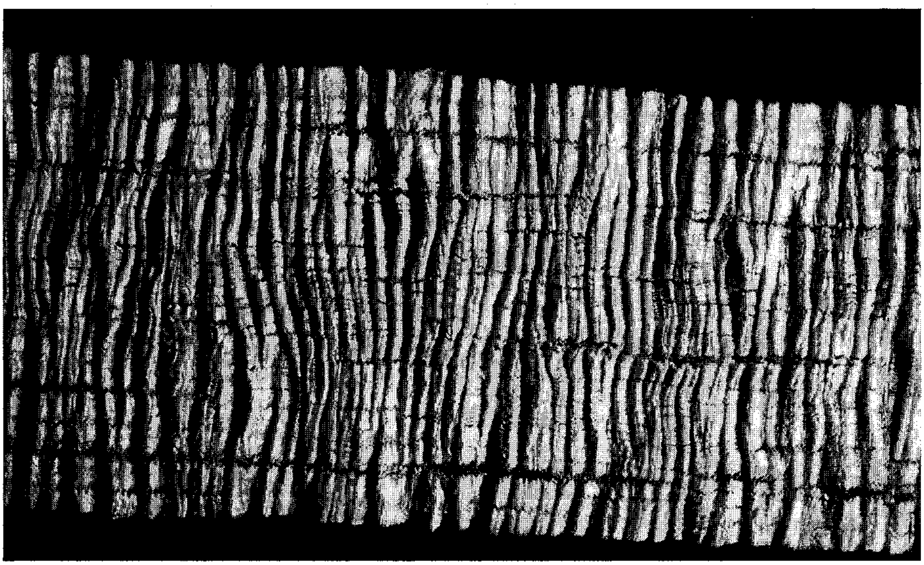

Fig. 8: Crimped filaments (width of photograph: 7 cm)

5.2.3 Characteristics of Filter Tow

The filter design and Tow processing depend on a variety of Filter Tow characteristics, the most important of which are:

Thickness of the Filaments (Denier per filament)

According to an old textile indicator, the thickness of a filament is defined by the weight in grams of 9000 meters of uncrimped fiber. Filaments of Filter Tows are manufactured in the range of 1,5 – 9 denier per filament.

Total Tow Mass (Total Denier)

The total weight in grams of 9000 meters of uncrimped Filter Tow is defined as Total Denier. Consequently, Total Denier divided by the denier per filament gives the number of filaments in the given Filter Tow. Thus, a Filter Tow can be easily described by its denier per filament and its total denier. The code 3Y35000 is for example used for a Filter Tow with 3 denier per filament, Y-shaped filaments and 35000 total denier, which says at the same time, that the Filter Tow contains 11670 filaments.

Cross Section of the Filaments

Y-shaped cross sections are standard for utilisation in Filter Tow, as this geometry represents the optimum for the filter weight/efficiency ratio.

Crimp Structure

As crimp structures are complicated to measure, Filter Tow crimp is defined by the so called crimp index. This is the length ratio of stretched Filter Tow (25 kg load) to its unstretched state (with 0,25 kg preload)

Moisture Content

According to the equilibrium conditions of water / Cellulose Acetate (see chapter 4.1.6), the moisture of Filter Tow is specified to 5-6% of water. The water content of the Filter Tow is important to avoid the generation of electrical charges which could possibly produce fly dust on the rod maker.

Lubricant Content

A lubricant is applied on the Filter Tow during spinning in order to reduce electrostatic charges on the rod maker. The lubricant consists of pharmaceutical grade mineral oil with an emulsifier, applied to 1% on Filter Tow.

Webbiness

The webbiness shows how regularly the Filter Tow filaments intermingle with each other. This parameter is visually checked by pulling the Filter Tow edges and inspecting the uniformity of the resulting web (see fig. 9)

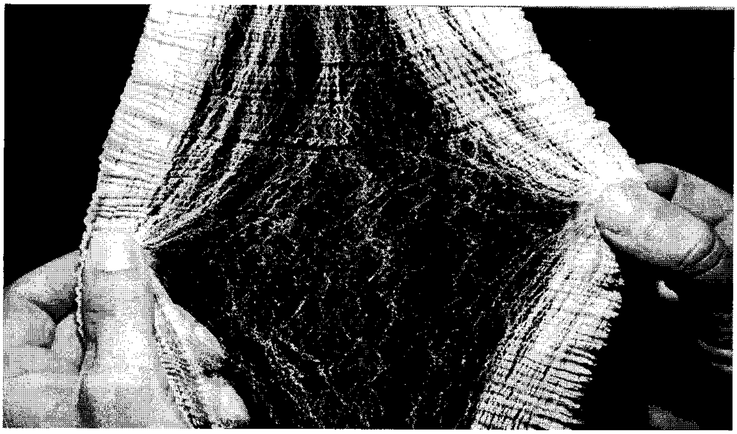

Fig. 9: A uniform Filter Tow webbiness is good for regular filter rod manufacturing.

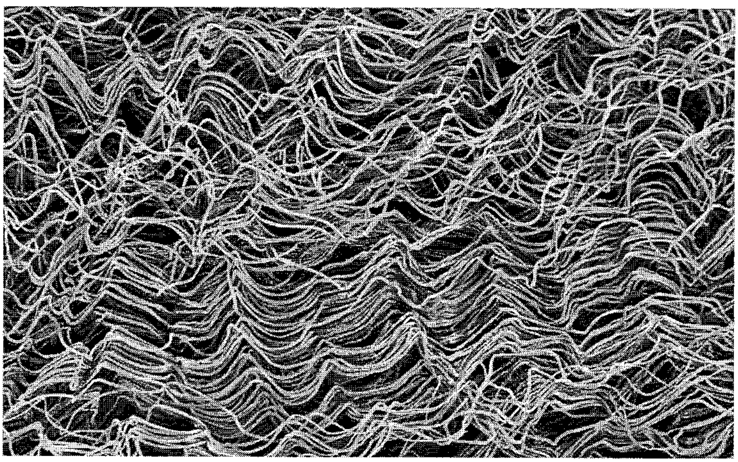

Fig.: 10: Scanning electron micrograph of a Filter Tow (width: 5 mm).

5.2.4 Filter Rods from Cellulose Acetate Filter Tow

The Function of the Filter Rod Machine

Filter Tow is processed in two stages in a filter rod machine:

1. The Filter Tow is bloomed as much as possible so that it develops its maximum filling capacity.

2. The bloomed Filter Tow is compacted into the shape of the future cigarette filter and surrounded by paper.

For the purposes of problem-free production and consistent quality, the filter rod manufacturers would naturally like the Filter Tow bales to run without jamming, tugging, or producing dust. The Filter Tow manufacturer achieves this by giving the Filter Tow a web structure and laying the tow in a carefully worked out pattern in the filling boxes.

The cohesion of the filaments must not be too strong, because optimal blooming of the Filter Tow requires that all individual filaments are disentangled and can shift against one another. Under these conditions to achieve maximum filling capacity, optimal pressure drop within the filter, and optimal hardness of the filter rod is achieved.

5.2.4.1 Blooming the Filter Tow

During the stuffer box crimping process, large groups of filaments are given a parallel crimping structure at the same point. This supports the cohesion of the Filter Tow. To achieve an optimal blooming of the Filter Tow, the filaments must now be shifted individually and the crimps against one another. This is accomplished in the filter rod machine under the application of two principles:

- Depending on the Filter Tow's webbiness, spreading jets driven by compressed air draw the Filter Tow apart, as much as possible.

- A system of paired feed and ratio rollers, running at different speeds and partly due to their screw thread-like surface only grasp parts of the spread out Filter Tow and stretch and shift the individual groups of filaments against each other.

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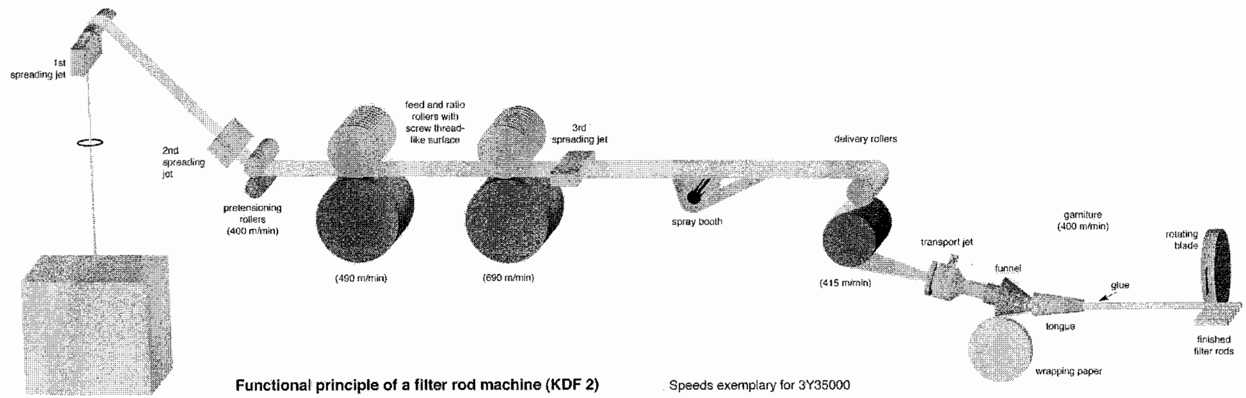


Fig. 11: Functional principle of filter rod machine

5.2.4.2 From bloomed Filter Tow to Filter Rod

The spread out Filter Tow with predominately individual filaments is now fed into the spray booth, in which rotating brushes create a fine spray of glyceryl triacetate, which is applied onto the acetate filaments.

The glyceryl triacetate plasticises the surface of the acetate filament which allows the filaments to stick together forming a three-dimensional matrix structure in the finished filter rod. This creates the necessary filter hardness for further processing which is necessary to meet the demands of the consumer.

In the next step, the Filter Tow is fed by delivery rollers into the transport jet driven by compressed air. The transport jet compacts the processed tow and feeds it into the tongue, which due to its funnel-like geometry compresses the Filter Tow to the desired diameter of the future filter rod. The Filter Tow bundle, together with the plug wrap paper strip, is then transported on a small garniture into a tube that sticks the paper with hot-melt adhesive. At the end of the tube the finished filter rods are cut by a rotating blade.

5.2.4.3 Hardening the Filter Rods

In the spray booth, the finely dispersed glyceryl triacetate droplets are applied onto the CA filaments. Each droplet plasticises the CA surface immediately and makes it sticky.

In the freshly compacted filter rod, when two such sticky filaments collide, they spontaneously remain stuck to one another. As a result of many such adhesive zones, a three-dimensional matrix structure of acetate fibres comes into being.

In the hours following the manufacture of the filter rods, the glyceryl triacetate diffuses evenly throughout the entire cellulose acetate; the adhesive zones become firm again - the filter hardens.

This hardening can also be measured macroscopically by observing the increasing hardness of the entire filter rod. After 15 minutes the fresh filter rods are hard enough to be processed in the cigarette maker.

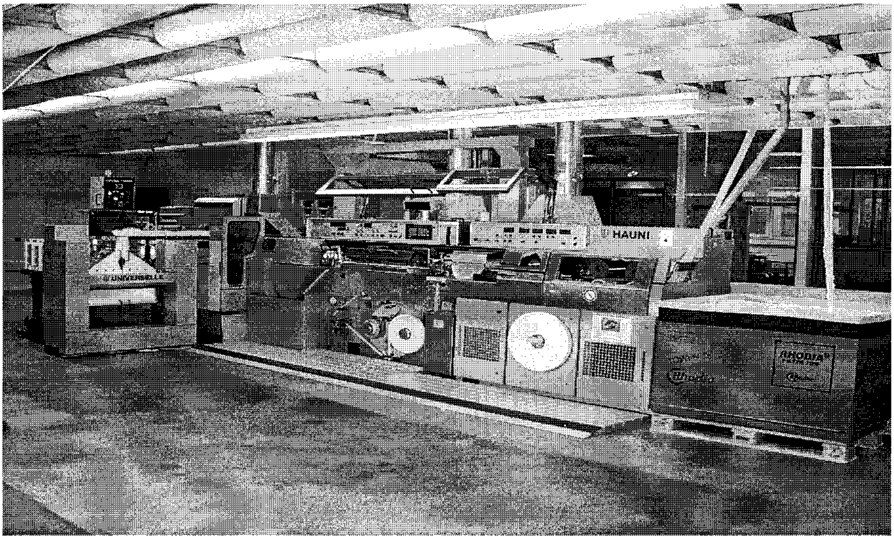


Fig. 12: Filter rod maker

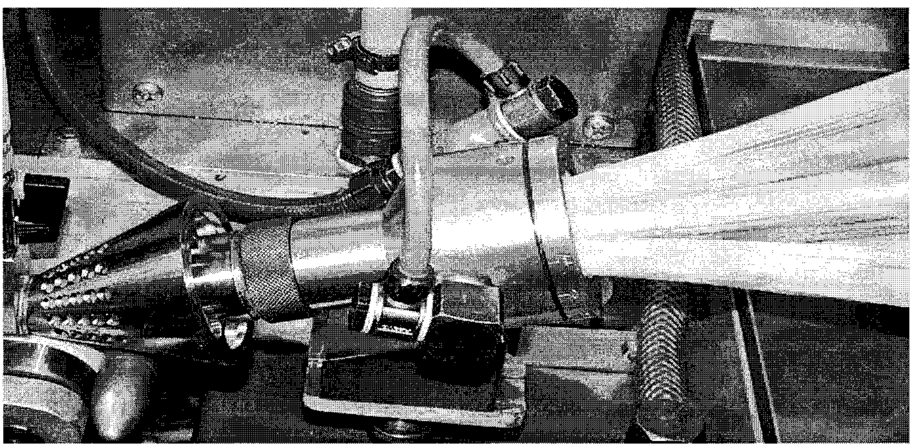


Fig.: 13: Filter Tow entering into the funnel of a rod maker.

5.2.4.4 The Filter Rod

The capability line of a Filter Tow - Orientation for the desired filter properties

When making a cigarette filter the cigarette manufacturer strives for an optimum between

- the pressure drop (approx. 50 mm water-column pressure),
- the desired tar retention (approx. 40 - 50%), as specified by the cigarette designer
- the hardness,
- the type of Filter Tow material,
- the diameter and length of the filter.

An important consideration for the construction of a cigarette filter is the so-called capability line of the tow, which describes what quantity of a Filter Tow (denier per filament, total denier) leads to a particular pressure drop.

Due to technological considerations the capability line is limited at the top and the bottom:

- At the minimum weight, the Filter Tow shrinks in the filter rod (recessed ends). The hardness becomes low and the retention small.
- At the maximum weight, due to the inadequate Filter Tow tension, the danger of roll wraps at the delivery rollers of the filter rod machine increases. Moreover, the pressure drop values show great variation.

How the Pressure Drop is influenced by the Denier per Filament and the Total Denier

The diagram (in fig. 15) shows the capability lines of different Filter Tows (denier per filament, total denier).

This indicates clearly that:

- The higher the total denier is the higher the pressure drop.
- For Filter Tows each with the same denier per filament, there is an almost continuous family of curves.
- The finer the denier per filament is, the higher the pressure drop with the same weight of acetate.

A saving in material related to a finer total denier of the Filter Tow unfortunately leads to a lower tar-retention, less hardness and problems with hot collapse.

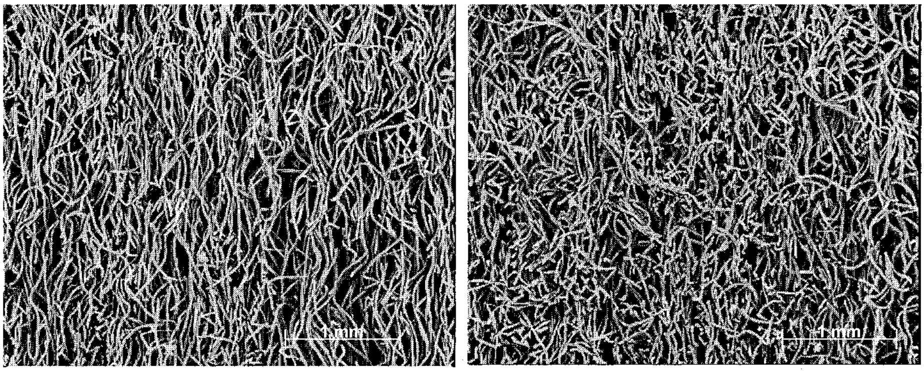
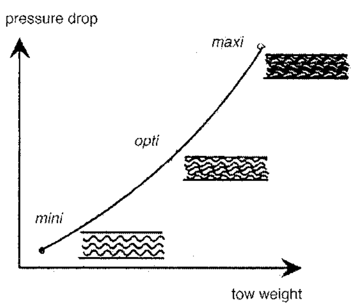


Fig. 14: Longitudinal section of filter rods from 3 Y 35000, left in "mini", right in "maxi"- setting of the rod maker. Magnification approx. 20 times. Clearly visible in the right picture is the higher filament density and the greater lateral orientation of the filaments. These crimps at right angles to the flow cause the considerably higher pressure drop.



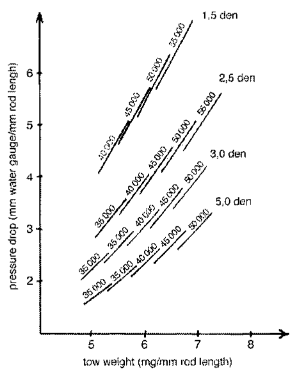


Fig. 15: Capability line of the Filter Tow corresponding to fig. 14.

Fig. 16: Capability line of various Filter Tows with different denier per filament and total denier.

How the Retention of Nicotine and Condensate is influenced by the Denier per Filament and Total ´Denier of the Filter Tow

The retention value of a filter indicates what percentage of a substance is retained by the filter. Experimental investigations on the filters yielded the nicotine and tar retention values summarised in fig. 17.

This can be interpreted as follows:

* There is a tendency for the retention values to increase with increasing pressure drop.
  This also reflects the expectation that more filter material leads to a higher retention capacity.
* The finer the denier per filament the higher the retention values are at the same pressure drop.
  The higher specific surface area of the fine filaments and the greater number of the fine filaments per weight unit are the reasons for this effect.

These relationships - useful for the development of light cigarettes, are integrated in special software programs available at the Filter Tow producers.

Hardness and Hot Collapse

The hardness of a filter rod made of cellulose acetate mainly depends on the following parameters:

- Amount of Filter Tow in the filter
  The more Filter Tow the denser the three dimensional network and the harder the filter.
- Amount of glyceryl triacetate
  The more triacetine the harder the filter;
  above 20% saturation effect - above 7% problems with hot collapse!
- How glyceryl triacetate is applied
  Larger droplets provide fewer adhesive sites.

- Moisture content of the Filter Tow

  Too much water acts as a plasticiser.
- Condition of the filter rod machine

  Badly processed tow reduces the hardness.
- Denier per filament

  The finer the filaments, the smaller the bending resilience and the softer the filter.

Many smokers want the filter to remain hard until the last draw and not to collapse under the influence of the ever-hotter and more moist smoke gases (hot collapse). The danger of hot collapse increases when the filter is soft as a whole and when it contains too much glyceryl triacetate.

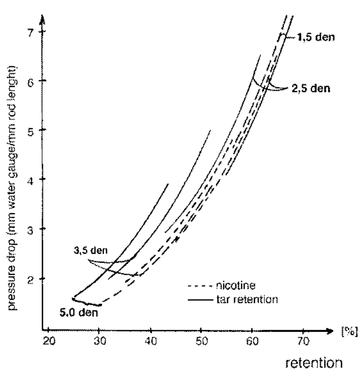


Fig. 17: How the retention of nicotine and condensate is influenced by the denier per filament and total denier of the Filter Tow.

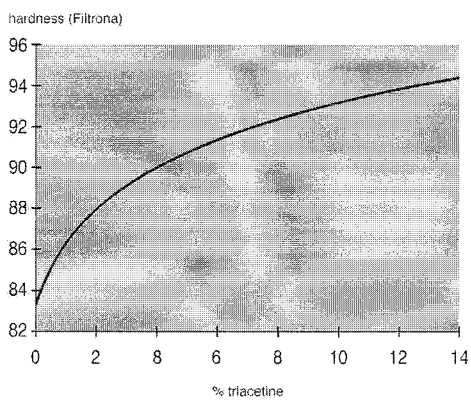


Fig. 18: Hardness and hot collapse.

5.2.5 The Action of the Acetate Filter

The major purpose of the cigarette filter is to remove about 50% of the cigarette smoke which consists of different fractions: a gas phase and an aerosol with semivolatile components and particulate matter [6, 7, 8].

There are different mechanisms for the deposition process of the smoke, depending on the size of the particles. The flow behavior in a cigarette filter is laminar: the volume flow through the filter is strictly proportional to the pressure drop between the two ends of the filter. In order to enable a better appreciation of the flow behavior, the flow curves in the graphs in fig. 19, 20-23 were drawn in one plane. These flow curves are parallel in the working range of the filter (pressure drop of approx. 50 mm water-column pressure). In the area surrounding the filament, the flow curves become closer to one another.

Filtration Mechanism 1: Escape of volatile substances by diffusion

Gases comprise of freely moving molecules. Their mean velocity is higher the higher the ambient temperature. Thus, a nitrogen molecule (80% of the air) at 25°C has a mean velocity of 0.5 m/s. The distance between these nitrogen molecules is approx. 200 times higher than their own diameter. Hence, the nitrogen molecules collide with their neighbors about 7 billion times per second, continuously changing their direction of movement.

The flow velocity of the cigarette smoke through the filter of approx. 0.7 m/min is about the same as the velocity of the molecules themselves. Thus, it is simple for the molecules to also move at right angles to the direction of flow (to diffuse).

This means that vaporised molecules of substances contributing to the aroma from the cigarette smoke can collide with the adjacent acetate surfaces and adhere to them.

The higher the acetate surface area and the more fibres per unit volume in the filter, the higher is the adsorption of volatile substances onto the filter.

Filter Mechanism 2: Removal of small smoke particles and droplets through Brownian movement

As a result of the collisions of numerous gas molecules, smaller smoke particles and droplets in the smoke are permanently diverted from the main direction of flow by the filter. The lighter the particles are, the more erratic their course.

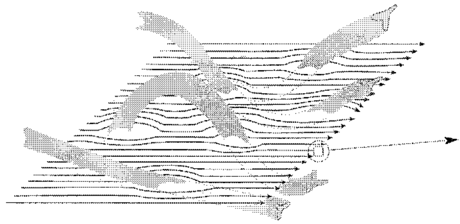


Fig. 19: Laminar flow of smoke gases in the filter. The flow curves always run around the acetate filaments.

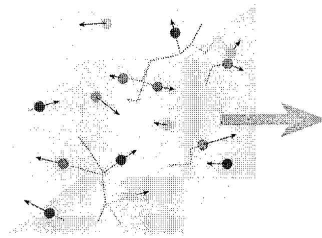


Fig. 20: A volume element of smoke gas, which passes through the filter with a mean flow velocity of 0.5 m/s. It contains gas molecules, which fly erratically with a mean velocity of 0.7 m/s.

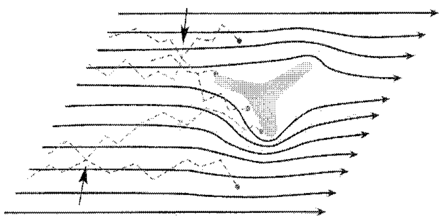


Fig. 21: As a result of mutual "jostling" (here indicated with arrows) the molecules can diffuse at right angles on the direction of flow and collide into an acetate surface.

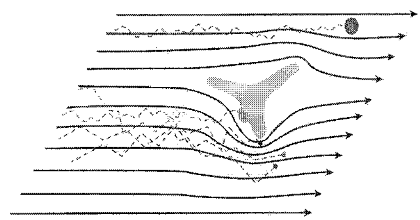


Fig. 22: Larger particles in the smoke gas can also be easily knocked permanently out of its flight path by collisions with molecules. As a result of this so-called Brownian movement, more particles make contact with the filter surface as more Filter Tow filaments are aligned at right angles to the direction of flow in the filter

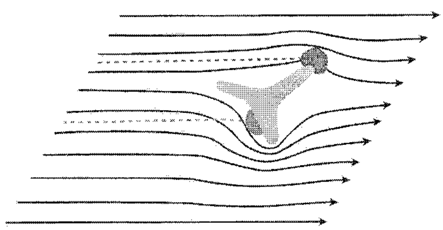


Fig. 23: In the case of heavy smoke particles and condensate droplets, the mass inertia of the particles becomes so great that they cannot follow the changes in direction of the filaments of flow around acetate fibres so that they strike the acetate filament.

This erratic movement can be observed under the microscope and is called "Brownian movement".

The Brownian movement contributes towards the droplets and smoke particles breaking away from the flow curves, which run around the CA fibres, and colliding with and adhering to the acetate surface. Due to this, the CA is gradually covered by a sticky layer of condensate. Volatile substances contributing to the aroma can evaporate again from this layer and less volatile substances can be deposited from the smoke.

The higher the fraction of fibres at right angles in the filter, the higher the precipitation of condensate as a result of the Brownian movement mechanism is.

Precipitation Mechanism 3:

Collision of larger particles as a result of mass inertia and effects of gravity

In the case of heavy smoke particles and condensate droplets, the mass inertia of the particles becomes so high that they cannot follow the changes in direction of the flow curves around the acetate fibres, and thus collide with the acetate filament. This type of filtration can also be improved by a larger fraction of filaments at right angles to the direction of flow.

Very heavy smoke particles can "precipitate" onto the tobacco or the filament material due to the effect of gravity.

5.2.6 Selective filtration of cellulose acetate filters

The selective filtration effect is definded as the capability of a filter material to remove preferentially a given substance. Several selectivity factors have been definded, for example the ratio of the smoke condensate filtration efficiency of the total particulate matter (filtered/unfiltered) to the filtration efficiency of a single smoke component [9]:

$$Sx = \frac{1 - R_{TPM}}{1 - R_x}$$

(R_{TPM} and R_x are the fractional retentions of TPM and smoke component x)

The chemical structure of cellulose diacetate with polar and nonpolar regions on the molecule is quite attractive for many molecules. Thus, the selective retention of many smoke components is an inherent characteristic of the filter material. As many of the absorbed smoke constituents are taste active, each filter material generates a special taste profile. The effects of selective retention for phenols are illustrated in fig. 24 for cellulose diacetate filter compared to a paper filter [10, 11].

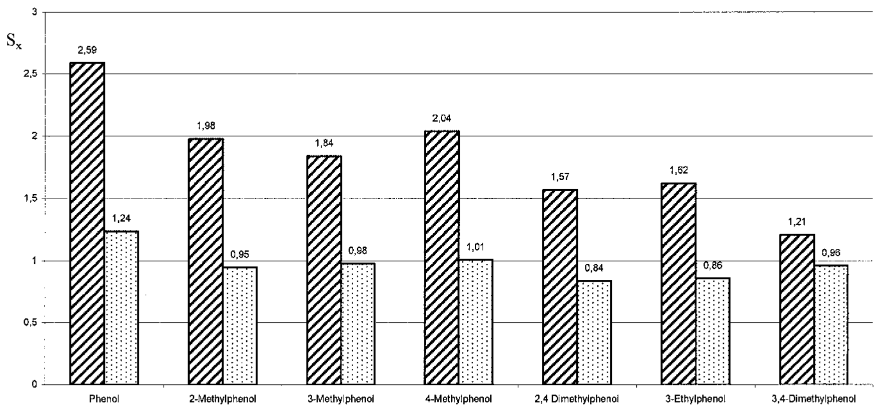


Fig 24: Retention of various phenols in cellulose diacetate A and cellulose B .
(S$_X$: Selectivity factor)

The results of a recent investigation of different types of filters (cellulose acetate and polypropylene) are shown in fig. 25.

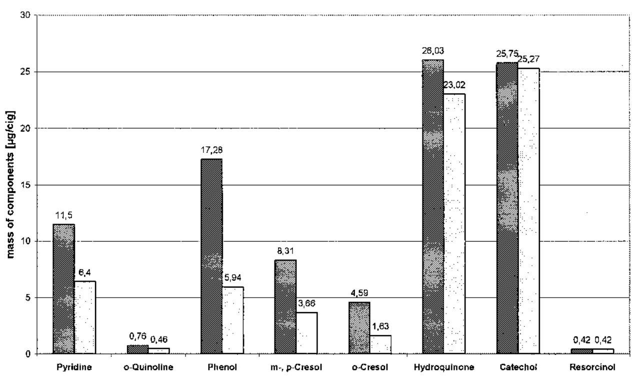


Fig. 25: Retention of various analytes in a polypropylene filter

Plasticisers in the cellulose acetate, such as triacetate increase the specific retention of phenols and other components considerably as they support the migration of those molecules into the cellulose acetate fiber. A good example is given in fig. 26 [12, 13]. In 1975 Morie, Sloan and Baggett described a relationship for predicting the selective removal by plasticized cellulose acetate filters [14]. This model was based in the assertion that for a smoke component to be selectively removed by a filter:

(1) a significant portion of the compound should be in the vapor phase

(2) the compound should have an affinity for the filter material.

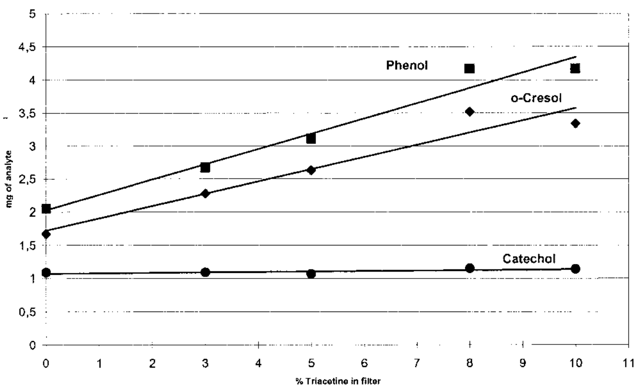


Fig 26: Effect of triacetine content in the cigarette filter on the selective filtration of phenol, o-cresol and catechol [12, 13]

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