

Polyvinyl chloride (PVC) is probably one of the most fascinating, most versatile, and oldest thermoplastic polymers. It is the polymer with which a person comes into contact within minutes of their birth: the bracelet bearing a newborn's name and birth date is commonly made of PVC. Products made of PVC accompany us through life—from toys to drinking water pipes. One of the most outstanding characteristics of PVC is its enormous longevity with an almost unchanged functionality.

■ 1.1 □ The Production of Polyvinyl Chloride (PVC)

For the production of PVC, a distinction can be made between an older process based on calcium carbide, which is converted into acetylene as a next step, and the modern process based on ethylene generated from petroleum or natural gas by cracking. As the carbide process is no longer of importance in Europe, though still utilized for example in China, it will not be covered in this section. The modern production of PVC can be described in a simplified manner (Fig. 1.1). The left-hand side of Fig. 1.1 depicts the cracking of petroleum or natural gas to make ethylene. On the right-hand side of Fig. 1.1, chlorine and sodium hydroxide (caustic soda) are produced by electrolysis of rock salt. Previously, the chlorine was considered to be a waste by-product whereas the caustic soda, a raw material for glass manufacture, was the target product. Today, chlorine is considered a target product in its own right.

Ethylene and chlorine are reacted to give ethylene dichloride. In a second step, the ethylene dichloride is processed to vinyl chloride monomer (VCM). The VCM is then polymerized in an autoclave under pressure, with the addition of initiators and further additives, to form PVC. The initiator forms radicals R^* , which start the polymerization reaction (Formula 1.1).

Temperatures range from 50 to 70°C and pressures range from 7 to 12 bar. Pre-stabilizers, mostly antioxidants, are often added before drying the reaction product. After drying, the PVC is ready to be shipped.

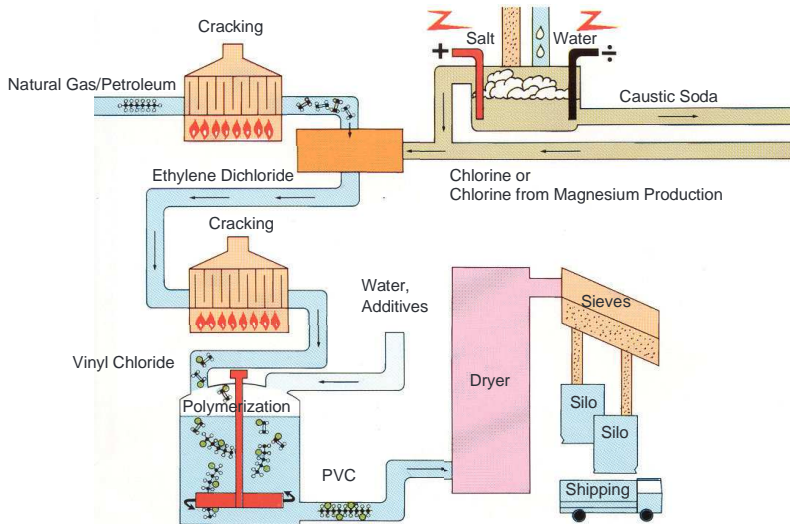
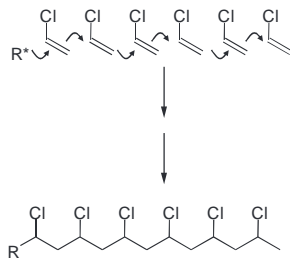


Figure 1.1 Schematic representation of the production of PVC [1]



Formula 1.1 Polymerization of vinyl chloride monomer (VCM) to PVC

As for all polymerization reactions, the resulting products are not uniform. They have different chain lengths and chain branching. The k -value was introduced as a simple reference value for the average chain length of the polymer: the shorter the average chain length, the smaller the k -value. The average chain length is determined by the reaction conditions during polymerization. In general, it can be stated that the k -value of PVC decreases with increased polymerization temperature and pressure. On the one hand, the k -value is related to the molecular weight of the polymer chains. On the other hand, it is also related to polymer properties such as softening temperature, stiffness, hardness, intrinsic stability, and modulus of elasticity.

There is a simple rule: the higher the k-value, the more viscous and tough the melt, the harder and stiffer the resulting product (for example, profile, pipe, film) will be, the more energy will be needed for processing, and the closer the processing conditions will be to the degradation temperature of PVC. With increasing k-value it becomes more difficult to process PVC. It is therefore not possible to process PVC with k-values in the range of 70 to 74 without prior addition of plasticizers. After the addition of plasticizers, the resulting end products are called “flexible” or “plasticized” PVC (p-PVC or PVC-P) products. It is possible to process PVC with k-values of 54 to 68 without addition of plasticizers. Such products are called “rigid” or “unplasticized” PVC (u-PVC or PVC-U).

VCM is not soluble in water. In order to disperse the monomer evenly in water, auxiliary additives have to be used. Historically emulsion polymerization is the oldest process and was first used in 1929. The initiators (for example peroxides and other per compounds) used in this case are water soluble. Emulsion polymerization can be run as a continuous or a batch process. In the batch process about 1% of emulsifier is added; the continuous process requires 2.5 to 3.0%. The emulsifiers are surface-active substances such as alkyl sulfonates, alkyl sulfates, or ammonium salts of fatty acids. These emulsifiers remain in the PVC after drying. The resulting polymerization product is the so-called E-PVC, and consists of very small particles in the range of 1 to 2 μm . The remaining amount of emulsifiers acts as an external lubricant and also gives the E-PVC good antistatic properties in the final products.

During the suspension polymerization process, the VCM is distributed in the water by intensive stirring. The radical initiators, for example azobisisobutyronitrile (AIBN), are soluble in the monomer. Suspending agents (used at 0.05 to 0.5%), such as polyvinyl alcohol or water-soluble cellulose, are added to prevent the agglomeration of the VCM droplets. This discontinuous process produces PVC particles of the size 50 to 200 μm , which are called S-PVC. If 0.01 to 0.03% of emulsifiers is used in addition to the suspending agents, the VCM is dispersed even finer, as a microsuspension, during the polymerization process. The resulting MS-PVC has particle sizes from 5 to 10 μm and is much finer than S-PVC. Pure S-PVC has a high purity, low water absorption, and good electrical properties.

If no water is used in the polymerization, the resulting polymer is called bulk or mass PVC, or M-PVC.¹ Because the initiator is dissolved in the VCM, the process steps of filtration and drying are no longer necessary. Products made from M-PVC appear more transparent and more brilliant than those made from S-PVC. The different PVC types are used in differing applications, according to their particle sizes and k-values; see Tables 1.1 and 1.2.

¹ In English the abbreviation m-PVC is also used for (impact) modified PVC. The designation o-PVC (or PVC-O) for oriented PVC pressure pipes is also commonly used.

Table 1.1 PVC Types and Their Applications

PVC Type	Particle Size	Predominant Applications
EPVC	1 to 2 μm	Plastisols, rigid and flexible applications
MS-PVC	5 to 10 μm	Plastisols
MS/ S-PVC	~50 μm	Extender PVC in plastisols
S-PVC	50 to 200 μm	Rigid and flexible applications
M-PVC		Transparent applications, various special applications

Table 1.2 k-Values of S-PVC and Application Areas

Application Area	k-Value of S-PVC			
	57–60	63–65	65–68	70–74
Pipes (compact pipes or outer skin layer)		+++	++	
Pipes (foam layer)	+++			
Pipe fittings (injection-molded products)	+++			
Ceiling/ wall panels, roller shutters	+	+++	++	
Edge banding (0.4 mm sheet)	+++			
Edge banding (2 mm profile)		+++		
Foamed technical profiles	+++	++	+	
Foam sheets	+++	+		
Geo membranes and water stops			++	+++
Door/ window profiles		+	+++	
Siding		+	+++	
Cables, hoses, tablecloth, shoe soles				+++
Cable channels		+++	++	
Rain gutters		++	+++	

+ recommended ++ very recommended +++ highly recommended

Other polymers, such as vinyl acetate or acrylate, can be polymerized with vinyl chloride. The resulting products are called copolymers. Different polymer chains can also be grafted onto the PVC chains (grafted PVC). A further possibility for modifying PVC is to add more chlorine to the polymer by a postproduction chlorination process. These PVC types with higher chlorine content than pure PVC are called C-PVC. They have a higher softening point, which results in more difficult processing behavior.

Another important criterion of PVC quality is the morphology of the PVC particles. The particles should be porous and irregular; the surface area should be as large as possible. Given these properties, a good absorption and dispersion of stabilizer one-packs and other additives is guaranteed. A too-even surface area of the PVC particles cannot properly absorb the additives, resulting in local decomposition of the PVC, thereby causing surface defects (pit marks, pitting, specks).

Furthermore, PVC should be free of any impurities. A standard test method is available to determine the number of black spots (impurities) in a given PVC sample: TSE EN ISO 1265. According to this standard, a maximum count of 60 black spots per sample is acceptable. However, this is considered too high for most applications, and a count of less than 25 spots is preferred. Moreover, a simpler, more practical test method exists for spotting impurities. A transparent glass beaker is filled with some water or ethanol or a mixture of these. Then a small representative sample of the PVC powder to be tested is added and the mix stirred to disperse the powder completely. Then the PVC is allowed to settle at the bottom of the beaker. The black spots in the settled PVC, viewed from below (observation is made easier by using a mirror, or even better, a magnifying mirror), are counted to assess the PVC quality. A few runs should be made to achieve higher statistical certainty. This average 'black spot' score should then be compared to an approved standard PVC grade, previously tested by the same method.

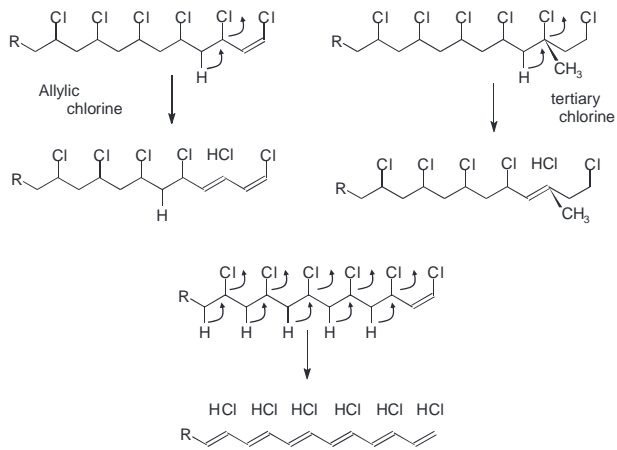
■ 1.2 Thermal Degradation of PVC

If the production of PVC progressed ideally, as represented in Formula 1.1, and resulted in linear polymer chains without any defects, processing of PVC powder would be much easier [2]. During polymerization, defects may occur [3]. The most important defects are

- tertiary chlorine atoms, which result from branch formation during polymerization (Formula 1.2), and
- allylic chlorine atoms, which form for example by termination of the polymerization reaction (Formula 1.2).

The degradation of PVC starts at these defect sites [4, 5]. Therefore, these chlorine atoms are also called labile chlorine atoms, and the site of the defect is called the initiation site of degradation. The degradation of PVC is called dehydrochlorination because hydrochloric acid (hydrogen chloride, HCl) is split off during the process. The split-off of HCl generates new defects. If no stabilizer intervenes, this process continues in a zipper-like fashion. Hydrochloric acid and conjugated double bonds form; the latter are also called polyene sequences. Once six to seven conjugated double bonds have formed, a slight yellowing of the PVC can be observed. This yellow discoloration grows darker with increasing length of conjugation, from red to brown and finally to black (Formula 1.2). The PVC is then called burnt.

In addition to the simplified mechanism discussed here, several others have been discussed. It should be noted, for example, that in addition to the ionic mechanism depicted in Formula 1.2 a radical degradation process can also be considered.



Formula 1.2: Degradation of PVC at allylic and tertiary carbon atoms due to heat or shearing

The influence of oxygen on the autocatalytic activity of the generated hydrochloric acid was investigated. It is further being discussed that longer conjugated double-bond systems can bind hydrochloric acid to form onium salts. This results in a deepening of the discoloration and is called halochromism. In addition to thermal degradation of PVC, shearing during processing and outdoor use of the finished products under the influence of light, air, and weather will also result in the degradation of the polymer.

These effects and mechanisms are most likely of secondary interest to the plastics processor. A detailed scientific discussion can be found in the relevant literature [2–55]. Of essential importance to the processor is that additives can counteract these degradation processes by preventing them or at least slowing them down, partially even reversing them.

This is what PVC stabilizers are for. Unfortunately, one universal stabilizer cannot fulfill all requirements. In most cases, stabilizers are blends of single additives that complement each other, often increasing the joint effect (synergism) and sometimes counteracting each other (negative synergism). Therefore, the following will give the reader a basic understanding of the single components that play, have played, and maybe will play a role in PVC processing.

■ 1.3 One-Packs

In most instances stabilizer blends are required to achieve the optimal PVC processing performance and the best properties for the final product. Further functions of the additives are

- substitution of labile chlorine atoms,
- shortening of polyene sequences,
- neutralization of HCl, and
- prevention of autoxidation.

In addition to the possibility of developing their own stabilizer solutions, the processor has the option to rely on formulated stabilizer-lubricant one-packs. These one-packs have the following advantages:

- All components (primary stabilizer, lubricants, flow modifiers, and other components) are included. In many instances, the one-packs are tailor-made, individual solutions.
- The cost of quality control is significantly lower because only one raw material, the one-pack, and not the individual additives, have to be tested.
- The stock-keeping is much simpler, as is the dosing and mixing in production.
- Any variability of the blends is reduced due to the fact that the minor components, the single additives, are preblended. A weighing error of the preblend has a much smaller effect compared to an error made with a highly lubricating single additive.
- Low-dust or dust-free one-packs improve plant hygiene for transport and mixing.
- Less packaging material is generated.
- The costs for new developments are lowered.
- In addition to one-pack deliveries, the one-pack supplier also ensures competent service.

Apart from having varying compositions adapted for specific requirements, one-packs are also delivered in various forms. The simplest one-packs are powder blends of individual additives. This allows virtually any combination of additives, and the powder is easily dispersed with nearly any mixing technique. Even liquids can be incorporated to a certain degree. A disadvantage is the dust generation during transport and dosing. This problem can be drastically reduced by some simple measures. One possibility is to pack the powder blends into bags. Very often the bag weight is adapted to the weight of the mix, and the complete bag can be dumped into the mixer. The bag material is chosen to be compatible with and remains in the final product. Another option is to compact the powders to granulates. This significantly reduces the dust issue. Granulating conditions are chosen to give a low dusting

but easily dispersible product. Quite clearly, this product form is not suitable for slow-running mixers. Pastes are powder blends that are mixed with plasticizers until a stable, often highly viscous mass is achieved. Consequently, the dosing of pastes requires special techniques.

In the case where dust-free products are required, tablets, flakes, and microgranulates are the delivery forms of choice. Of these, tablets are the most appealing. In most cases, these one-packs are based on a melt process. Because of this, the raw material combinations and the total amount of nonmelting products are more limited than in powder blends. The dispersion is done in high-speed mixers (Fig. 1.2). Liquid stabilizers, excluding tin stabilizers, are often a complex solution of additives in solvents and are mostly used in plastisol and calender applications.

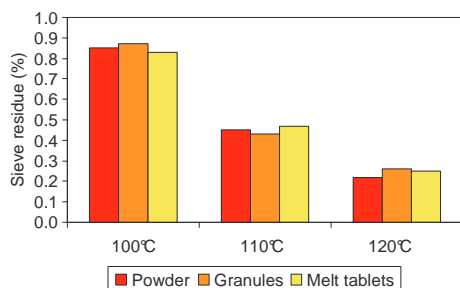


Figure 1.2 Studies on dispersion as a function of delivery form and mixing temperature

1.4 Heat Stabilizers for PVC

Heat stabilizers are based on

- metal-free, organic compounds,
- alkaline earth metal salts (mainly calcium or barium) in combination with cadmium or zinc salts (mixed-metal stabilizers),
- organotin compounds,
- rare earth metal salts, mainly based on lanthanum, and
- basic and neutral lead salts.

The 1990s saw fairly extensive discussions about the use of heavy metals for stabilizing PVC. We therefore want to examine the question here in more detail: What actually is a heavy metal?

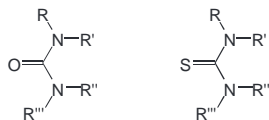
Scots have a multitude of expressions for rain [56]. Eskimos have 27 words for snow [57]. It is similar with heavy metals. Mankind has currently more than 40 definitions for this term, heavy metal [58]:

- The general public sees heavy metals as materials dangerous for humans and for the environment as a whole.
- There are currently 13 definitions based on the density of metal. These mention densities in the range of 3.5 to 7.0 g/mL. The most commonly used (scientific) definition is: a metal with a density > 4.5 g/mL is a heavy metal [59]. In this case even titanium, having a density of 4.506 to 4.508 g/mL, would be considered a heavy metal.
- Eleven definitions are based on the atomic weight. In the extreme, everything with an atomic weight higher than sodium is considered a heavy metal [60]. By this definition magnesium, aluminum, and calcium would be heavy metals.
- There are five definitions from the perspective of a chemist, and two in a biologist's view, which relate to the positions in the periodic table, the atomic number.
- Another five definitions of this term relate to various other chemical properties.
- Two definitions refer to toxicological principles.
- Probably the oldest definition was coined in 1884 and is quite graphic: "guns or shot of large size."
- Based on the definition of Directive 67/548/EEC, the elements antimony, arsenic, cadmium, chromium(VI), copper, lead, mercury, nickel, selenium, tellurium, thallium, tin, and their compounds are heavy metals.
- "Heavy Metal" is also a style of music.

The term heavy metal is misleading. Not every heavy metal is poisonous. Iron and zinc are essential, vital elements.

1.4.1 □ Metal-Free Base Stabilizers

Metal-free stabilizers have enjoyed something of a renaissance in recent times. The reason for this was the discussion of stabilizer systems containing heavy metals (see above). Metal-free, organic stabilizers were suggested for PVC at about the same time as lead stabilization [61, 62]. Urea and its derivatives were already published in 1937 [63] (Formula 1.3). In addition to the "normal" urea, the sulfur-containing thiourea (Formula 1.3) was also investigated. Years later, diphenylthiourea gained commercial importance as a stabilizer for producing E-PVC films by the Luvitherm process. Various (thio-)ureas were compared in a calcium-zinc test formulation. The calcium-zinc formulation was chosen to give the PVC a minimum basic stability.

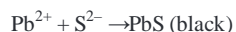


Formula 1.3 □ General structure of ureas (left) and thioureas (right); R, R', R'', and R''' can be identical or different substituents

Table 1.3 □ Comparison of Several Substituted (Thio)ureas for Thermostability, Early Color (YI 0), and Color Hold (YI 30). (Dosage Was 0.1 phr in a Formulation of 100 phr PVC [k = 68], 2 phr Chalk, 1 phr Titanium Dioxide, 1 phr Calcium Stearate, 1 phr Zinc Stearate, 0.5 phr Pentaerythritol, 1 phr Paraffin Wax [64]. Oven Stability in Minutes; YI 0 and YI 30 = Yellowness Index after 0 and 30 min (in a Thermo Oven))

Urea	Oven Stability [min]	YI 0	YI 30
none	60	18.4	44.6
Urea (unsubstituted)	45	17.0	35.5
N-Ethyl-	25	20.6	
N,N'-Dimethyl-	30	12.3	59.6
N-Benzyl-	30	13.5	68.4
N-Phenyl-	40	9.7	41.2
Morpholinyl-	30	18.1	64.2
N,N'-Diphenyl-	35	18.5	41.2
N,N'-Diethylthio-	15	31.8	
N,N'-Dibenzylthio-	20	16.5	
N,N'-Diphenylthio-	25	11.4	
N,N'-Di-n-butylthio-	20	22.4	
Dicyandiamide	45	11.4	55.1

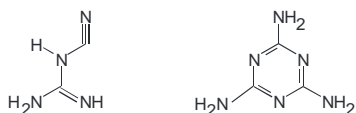
As the results in Table 1.3 show, various (thio-)ureas improve early color and color hold but decrease long-term thermostability in combination with zinc. It should also be noted that thioureas form black discolorations in combination with lead stabilizers. The reason for this is the formation of black lead sulfide (Formula 1.4).



Formula 1.4 □ Formation of black lead sulfide

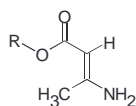
Dicyandiamide is the dimer of cyanamide. Dicyandiamide was used as a PVC stabilizer as early as 1942 [65]. From a chemist's perspective, dicyandiamide (Formula 1.5) can be seen as a derivative of urea. It shows structural similarities to guanidine and also to 4-aminouracil. Dicyandiamide is also a chemical precursor of melamine (Formula 1.5), which is the trimer of cyanamide. In PVC it behaves similar to urea;

see Table 1.3. Also, melamine derivatives are used as costabilizers for PVC, especially in flooring applications.

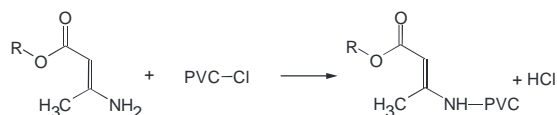


Formula 1.5 Structures of dicyandiamide and melamine

β -Aminocrotonic acid derivatives (Formula 1.6) were probably already mentioned as PVC stabilizers before 1961 [66]. They stabilize not only E-PVC but also S- and M-PVC. According to theoretical modeling, aminocrotonates substitute labile chlorine atoms at the PVC-chain; see Formula 1.7 [67]. Further literature [68] shows that, in addition to the effects mentioned before, aminocrotonates can also bind escaping hydrochloric acid. The effectiveness of aminocrotonates as stabilizers is relatively good, but the early color stability is only modest. Theoretically, aminocrotonates can be viewed as nitrogen-containing 1,3-dicarbonyl compounds; see also Section 1.5.3 and Formula 1.29. Typical examples are butyleneglycol diaminocrotonate (BGAC) and thioethyleneglycol diaminocrotonate (TGAC). The efficiency of aminocrotonates can be improved significantly in combination with synergists like calcium-zinc soaps or epoxides. A potential disadvantage of aminocrotonates is that small amounts of ammonia can be generated during processing [69].



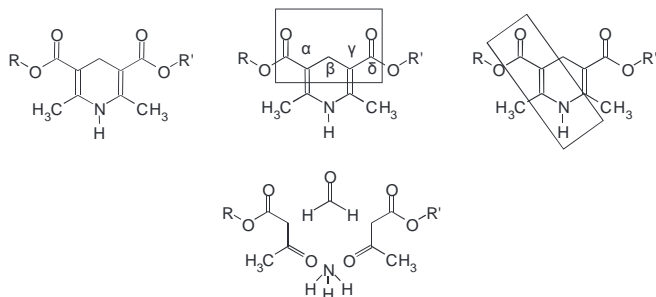
Formula 1.6 Structure of aminocrotonates



Formula 1.7 Stabilizing mechanism of aminocrotonates

Historically, dihydropyridines (DHP) are relatively 'young' metal-free basic stabilizers for PVC [70]. Depending on the chemical perspective applied, they can be identified as

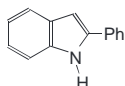
- δ -diketones,
- β -aminocrotonates, or
- derivatives of 1,3-dicarbonyl compounds (due to their synthesis from 1,3-dicarbonyl compounds, formaldehyde, and ammonia); see Formula 1.8.



Formula 1.8 □ General structure of dihydropyridines (top left), as δ -diketone (frame, top middle), as β -aminocrotonate (frame, top right), and as β -diketone ("exploded" display, bottom)

They probably stabilize PVC in a way similar to aminocrotonates or uracils; see Formula 1.7 and Formula 1.11.

In the early days, the thermostability of calcium-zinc stabilizers alone was not sufficient for the production of mineral water bottles. Because of this, α - or 2-phenylindoles (2-PI) were added as costabilizers, especially in France [71]; see Formula 1.9. 2-Phenylindole requires no further catalyst to substitute the labile chlorine atoms of the PVC polymer. A disadvantage of this compound, though, is that it has a tendency to strongly discolor after only a short period under radiation, for example in sunlight. The migration of 2-phenylindole can also cause issues. In contrast to the light sensitivity, the migration problem can easily be resolved by introducing alkyl substituents into the molecule.



Formula 1.9 □ Chemical structure of 2-phenylindole

The uracils depicted in Formula 1.10 were first mentioned as stabilizers for PVC in 1966 [72]. In a way they are fascinating compounds, because they combine the structural elements of urea and those of aminocrotonates; see Formula 1.10. A pessimist would expect a negative synergism: the bad early color of the aminocrotonates and the weak long-term thermostability of urea. In reality the system retains the positive properties of each: the good early color of the urea and the good long-term thermostability of the aminocrotonates. The uracils constitute an intramolecular, or, expressed in simpler terms, an internal synergism of two molecules. Uracils are able to substitute unstable chlorine atoms in the polyvinyl chloride chains, similar to aminocrotonates. This mechanism was proven in the literature [73] (Formula 1.11).

2

Additional PVC Additives

■ 2.1 ■ Lubricants

2.1.1 ■ Introduction

The lubricants, often also inaccurately referred to as waxes, are another important class of PVC additives. They may not compare volume wise to, for example, the fillers but are certainly in a class of their own with regard to functionality. Stabilizers and lubricants are not only applied jointly by using a stabilizer-lubricant one-pack. On one hand, there is virtually no PVC process or application that does not need lubricants. On the other hand, many stabilizers such as metal soaps (see also the section on metal soaps next and in Section 1.4.2) also have, in addition to their stabilizing rheological properties.

Lubricants influence the following:

- the overall processing window, in general as well as in important detail,
- the plastification, and subsequently also,
- the mechanical properties of the extrudate,
- the wall-slipping behavior,
- the metal release in general,
- the torque during extrusion,
- the pressures during extrusion,
- the melt temperature,
- the melt viscosity,
- the melt homogeneity,
- the melt elasticity,
- to some degree the dynamic stability,
- the surface quality of the extrudate,
- the gloss,

- the plate-out behavior (see also Chapter 3),
- the die swell, and by that also
 - the final dimensions of the extrudate
 - the take-off tension needed to pull the profile or pipe through the calibration, and by that,
 - the shrinkage
- the welding behavior,
- the incorporation and dispersion of inorganic/nonmelting components, e.g., filler,
- the glass transition temperature [1, 2] and by that the VICAT softening point and ductility,
- the density of the final product,
- the transparency of the final product,
- the extrusion output, and last but not least,
- the price of the final product.

From the number and the complexity of influences it can be rightly concluded that, similar to the so-called butterfly effect for the weather [3], changes in the lubricant balance can not only have the intended effects, but also an unlimited number of unintended side effects which often cannot be predicted.

Like stabilizers, lubricants cannot be characterized by a single, generally applicable chemical formula. Too various are the functions of individual lubricants, mainly in production but sometimes also affecting the final product. Because of this, also the chemistry behind lubricants is just as diverse.

The definition of the term waxes by the Deutsche Gesellschaft für Fettwissenschaft (DGF, German Association for Fat Sciences), commonly encountered in the literature, was initially conceived for the historically most important application, care products [4]. Nevertheless, it can also be used in many areas of the plastics industry. Accordingly, many lubricants can also be characterized by the following properties. A substance is called a wax, when it:

- can be kneaded at 20°C,
- is of solid to brittle hardness,
- has a coarse to microcrystalline structure,
- is translucent to opaque but not glass-like,
- melts above 40°C without decomposition,
- has a low melt viscosity only a few degrees above the melting temperature,
- has a strongly temperature dependent consistency and solubility, and
- can be polished under slight pressure.

“...what you see at the scene of a ...‘problem’ is frozen in time, it is no longer a moving, living dynamic. You can create several stories about this still life; but these are only theories. You, like ‘a detective’ ...can assemble hard facts and solid scientific evidence, and still draw the wrong conclusions. Add to this, a few lies and red herrings and people who are trying to help but make mistakes. Plus people who tell you what you want to hear, consistent with your theory, and people with hidden agendas, and ...‘other persons,’ ...who may have planted false clues. Through all this mess of contradictions, inconsistencies, and lies is the truth.”[1]

■ 3.1 ■ Literature Review of Plate-Out

The Eskimos may have many expressions for snow and ice [2], but none for plate-out. The Africans are surprised that it can be so difficult to name such a simple phenomenon as snow. Chemists, on the other hand, are astonished that such a vast field of effects as plate-out is only described by one word.

Plate-out is a seemingly normal issue in PVC processing [3–10]. Nevertheless, there are only a limited number of publications about this phenomenon. The reasons, influencing factors, and mechanisms of plate-out have only been inadequately explained so far. Bos et al. defined plate-out “as uncontrollably occurring, often quite disruptive deposits or coatings, which form after a longer production period on the hot or cold metal surfaces of a processing line” [4]. The plate-out issue started to attract more attention in the late 1970s to the early 1980s [3, 5, 6].

Parey discusses the influence of the mixing conditions and the surface properties of the PVC [3, 5]. However, these influence factors were not considered by any other authors. Parey also suggests that PVC formulations stabilized with liquid stabilizers show less tendency for plate-out than those with solid stabilizers. Bos et al. were most likely the first to introduce the differentiation between plate-out in the tooling and plate-out in the calibration [4].

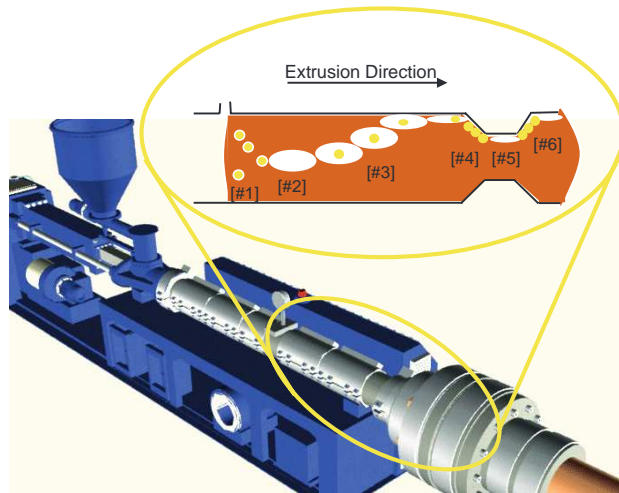


Figure 3.1 Plate-out formation in the tooling/ die (extruder drawing from [11])
 [#1] inorganic particles, such as fillers, (white) pigments, inorganic costabilizers
 [#2] nonpolar heterogeneous phase, like insoluble paraffin or polyethylene waxes
 [#3] coating of inorganic particles with the phase #2 and migration to the interface between polymer melt and hot metal surface
 [#4] deposition of inorganic particles in the compression zone of the tool
 [#5] deposition of inorganic particles in the decompression zone of the tool
 [#6] onward migration of phase #2

Lippoldt suggested the probably most accepted mechanism for the formation of plate-out [6]; see Fig. 3.1. The theory was developed for tin-stabilized systems and is based on the fact that some organic components only have a limited solubility in the hot PVC melt. It is assumed that these less soluble components, such as paraffin waxes, separate as a heterogeneous phase from the melt [#2]. These separate phases, interacting with the volatile tin stabilizers, can then transport inorganic particles [#1] to the metal/polymer melt interface [#3]. In areas of compression [#4] and decompression [#5] the inorganic components are deposited and act as triggers for further deposits, whereas the organic phase, acting as release agent between the metal and the melt, continues to move in the direction of the extrusion [#6].

Holtzen and Musiano investigated the influence of the polymer melt rheology in various tooling setups to identify the exact areas in which the plate-out actually forms [7].

Leskovyansky discusses a possible link between the occurrences of plate-out and oxidized metal surfaces [8]. Bussman and Kerr investigate in a similar direction, but with calcium-zinc stabilized PVC [9]. They attribute the formation of plate-out to the oxidation of the steel extruder barrel and the associated rougher surface into which excessive lubricants may migrate.

Pfister and Schlumpf concluded from roll mill experiments that natural calcium carbonate counteracts plate-out formation [12]. Kronos published in 1993 that there is no indication of a direct influence of titanium dioxide pigments on the formation of plate-out [13]. However, the overall compatibility of all components of a PVC formulation (polymer, pigments, fillers, stabilizers, lubricants, release agents, plasticizers) plays an important role. As an example, the exchange of only a stabilizer may result in the need to reformulate in order to avoid the formation of plate-out.

In many instances the tendency for plate-out formation can be reduced by adding certain lubricants (for example, 12-hydroxystearic acid) or by using about 2% (in relation to the total formulation) of natural or precipitated chalk. The addition of small amounts of fine silica or of acrylate processing aids has also been shown to reduce plate-out.

Another, often underestimated, influence on the occurrence of plate-out is related to the production and storage and aging of compounds or dry blends. It could be shown that for a compound with a given tendency for plate-out, the processing properties could be improved if prior to processing a certain storage time ("aging") was observed. A possible reason for this could be a change in the grain structure of the PVC compound over time.

The general processing conditions (barrel temperature, mass temperature, melt throughput, compression ratios in the tooling, geometry of the tooling, materials, and surface properties of the tools) also play a role. As an example, the findings of the Institute of Plastics Processing (IKV) at RWTH Aachen University are shown in Figs. 3.2 and 3.3. They display the influence of temperature and screw speed on plate-out formation: an increase is found with increasing temperature and a reduction at higher screw speeds. Figure 3.4 reveals that by increasing the titanium dioxide pigment concentration from 3% via 4.5% to 6% the pressure and torque increase, whereas the plate-out tendency is significantly reduced.

Almost all research work agrees that the plate-out consists mainly of inorganic substances, such as titanium dioxide, chalk, or basic (lead) stabilizer components. Organic compounds, for example calcium stearate, lubricants, plasticizers, and also PVC itself are rather underrepresented. It is safe to assume for any plate-out in the tooling that its composition will not reflect the overall dry blend formulation.

Occasionally it has been reported that the use of titanium dioxide or chalk has reduced plate-out. This is said to be attributed to the abrasive properties of these materials [4, 9, 10, 12, 13].

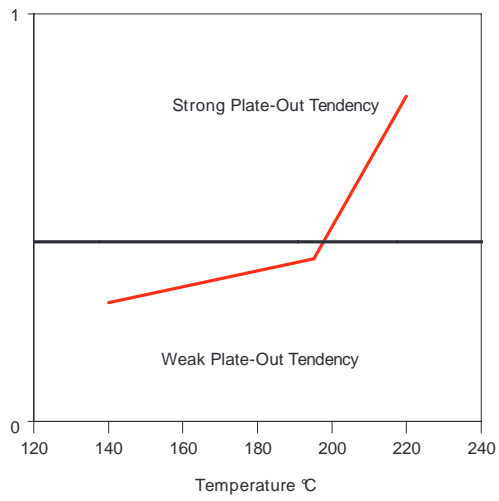


Figure 3.2: Plate-out as a function of temperature [13]

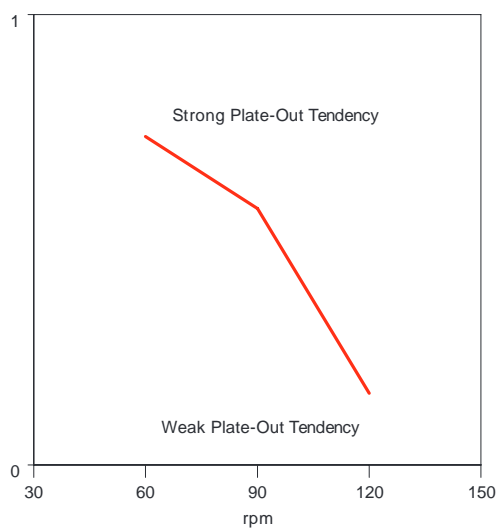


Figure 3.3: Plate-out as a function of screw speed [13]

4

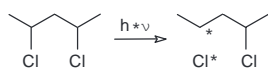
Uncharted Territory in the Use of PVC Products: Photo Effects

In order to better understand this chapter it is recommended that one first read the introduction to photochemistry and the remarks about titanium dioxide in Section 2.4.

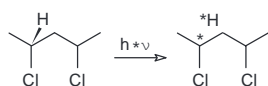
■ 4.1 Literature Review of Photochemical Degradation of PVC Products

4.1.1 Photochemical Degradation of PVC

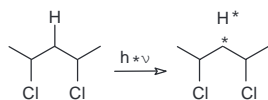
In theory, the photochemical degradation of PVC is comparable to the thermal degradation. Nevertheless, this author is convinced that thermal degradation is mainly based on an ionic mechanism, whereas photo-oxidative degradation mainly follows a radical principle. To investigate the photochemical degradation of PVC products one must further differentiate between the light absorption by the PVC itself and that by another molecule, for example titanium dioxide. In the case of light absorption mainly by the titanium dioxide (see Fig. 4.19) a variety of different radicals may be formed (see also Fig. 4.19). If the PVC mainly absorbs the light itself, the first step is the generation of radicals according to Formulas 4.1 to 4.3 [1]. For the second step it is almost irrelevant which radicals are actually formed. It is only important that the abstraction of a hydrogen atom, the so-called H-abstraction, is thermodynamically possible. The most likely second step is the formation of an isolated double bond by H-abstraction according to Formula 4.4 (this formula is wrongly presented in [1]). A mechanism according to Formula 4.5 is also theoretically possible. The common understanding is that this initiates the continuing, photochemically or thermally induced, degradation of PVC by a zipper-like mechanism.



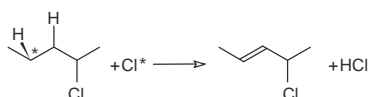
Formula 4.1 □ Light absorption by the PVC chain and resulting cleavage of a C-Cl bond



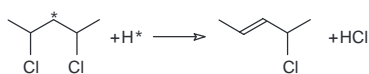
Formula 4.2 □ Light absorption by the PVC chain and resulting cleavage of a C-H bond



Formula 4.3 □ Light absorption by the PVC chain and resulting cleavage of a different C-H bond



Formula 4.4 □ Formation of a double bond by reaction of a chlorine atom with a polymeric radical (hydrogen abstraction)



Formula 4.5 □ Formation of a double bond by reaction of a hydrogen atom with a polymeric radical (chlorine abstraction)

This “zipper” process results in conjugated double bonds, also called polyene sequences. Naturally, these reactions also depend on the detailed chemical structure as well as the temperature. The formation of these polyene sequences can be observed by the following methods:

- UV-VIS spectroscopy [1], by which the absorption maxima are correlated to the number of conjugated double bonds (Fig. 4.1, Table 4.1),
- FTIR investigations of the double-bond absorption bands, or
- Raman spectroscopy investigations [2–5].

For these measurements we stored unstabilized PVC at 70°C and recorded Raman spectra after defined periods of time (Figs. 4.2 and 4.3). The most interesting area is between about 1000 and 1600 cm⁻¹. The Raman signal for the C-C single bonds is at about 1100 cm⁻¹ and for the C=C double bonds at about 1500 cm⁻¹. The latter is missing for the “virgin” PVC in Figs. 4.2 and 4.3. As the PVC without stabilizer is increasingly thermally stressed, the Raman signal at 1500 cm⁻¹ grows little by little.

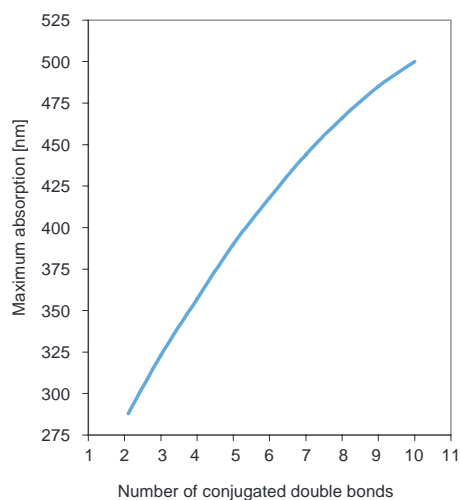


Figure 4.1 □ Correlation of UV-VIS maxima and the number of double bonds in polyene sequences [1]

Table 4.1 □ UV-VIS Maxima of the Polyene Sequences (n = Number of Double Bonds) [1]

n	Isomer													
3	Triene	240	248	257	268									
4	Tetraene			267	278	290	304							
5	Pentaene				279	290	304	317	334					
6	Hexaene						300	313	328	344	364			
7	Heptaene							316	332	350	368	390		
8	Octaene								332	349	367	386	410	
	Average	240	248	257	268	279	290	303	315	332	348	366	388	410

Interestingly, the signal for the C–C single bonds also increases (see Fig. 4.3). This is a proof that conjugated double-bond sequences form during degradation. During this experiment it is also interesting to note that, although after an hour at 70°C conjugated double bonds have formed, no discoloration of the PVC could yet be detected. This fact highlights how sensitive the Raman spectroscopy is to polyene sequences. In general, it is accepted knowledge that about seven conjugated double bonds are necessary to show up as a visible discoloration of the PVC or yellowing. The data in Table 4.1 support these experiences. The next question is: How many polyene sequences are needed to lead to black discolorations? According to the literature [6], the maximum number is at about 20 to 65 conjugated double bonds.

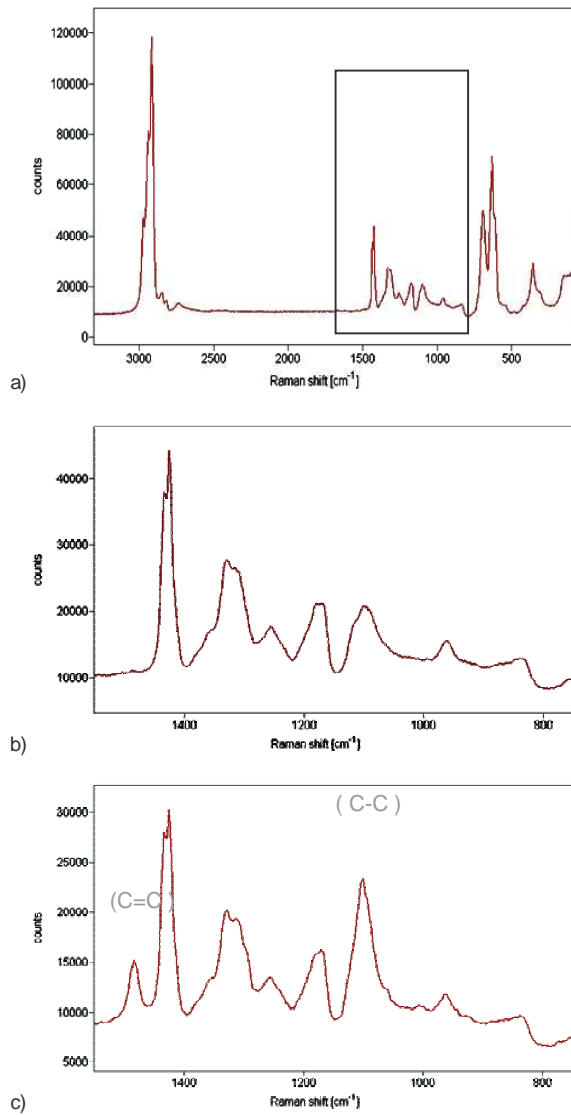


Figure 4.2 Raman spectrum of unstabilized PVC; thermally unstressed as overall spectrum a) and in detail b), and after thermal stress, in detail c)

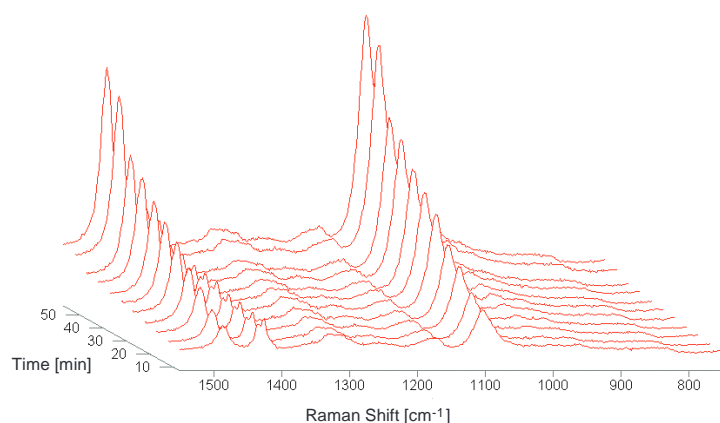


Figure 4.3 Raman spectra of unstabilized PVC at 70°C as a function of the irradiation time

Next to the fact that with every additional conjugated double bond the absorption behavior is changing (Fig. 4.1, Table 4.1) the oxygen biradical will also interfere with the degradation process. The polyene sequences and most likely the resulting PVC carbon chain will also be oxidized by these oxygen radicals. This then results in an interruption of the polyene sequences, causing a shift of the absorption bands to shorter wavelengths. In the end, the PVC will be decomposed to water, carbon dioxide, and hydrochloric acid. This decomposition, though, only applies to a depth of about 20 μm in the presence of titanium dioxide but will continue to a depth of 400 μm in its absence.

In this context, the investigations of Rhone-Poulenc, published in a series of papers, are of interest. In the first part of the series [7], Anton-Prinet et al. report the following findings. The majority of any stabilizers in the thinner layers disappears within the first days. As the stabilizer is spent, the number of polyene sequences increases dramatically. Associated with this is a loss of mass due to the continued loss of HCl (dehydrochlorination). No significant formation of polyenes is observed before all of the stabilizers are consumed. Only in the top thin layers ($\sim 80 \mu\text{m}$) is the oxidation reaction diffusion controlled. The majority of the absorbed oxygen is converted into carbonyl and hydroxyl groups. Carbonyl and hydroxyl group formation seems to appear only at the end of the stabilizer consumption. The oxidation is accelerated by increasing the temperature. The formation of polyene sequences is catalyzed by the evolving HCl. The polyene formation is more temperature dependent than the oxidation, and this is possibly caused by a nonphotochemical character of the reaction. The chain reaction can be quenched by the combination of radicals, reaction of oxygen with macromolecules, or by reaction of Cl^* radicals with CHCl groups.

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