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Comparison of heat, UV and radiation curing

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Strahlenhärtung

Zusammenfassung

Von den beiden Anwendungsformen der Strahlenhärtungsverfahren im Produktionsbereich, Elektronenstrahlen und UV, die zu Beginn der 70er Jahre mit eher optimistischen Prognosen versehen wurden, konnte sich in der Praxis UV im Bereich der Holz- und Folienbeschichtung bewähren, während sich die Härtung mit Elektronenstrahlen vor allem bei neuen Produktionsverfahren durchzusetzen scheint. Nach einer Aufzählung von Anwendungsvorschlägen der Strahlenhärtung und einer Gegenüberstellung der Vor- und Nachteile dieser Technologie erfolgt anhand einer Zahl von konkreten Anwendungsfällen unter Hervorhebung der Unterschiede zu konventionellen Verfahren jeweils eine Beschreibung der technischen Merkmale der Verfahren sowie eine Kalkulation der Produktionskosten, wobei das Konzept der Kalkulation dem Fachmann durch die Einsetzung anderer Produktionsparameter, Investitionsoder Energiekosten eine individuelle Kostenabschätzung ermöglichen soll.

Radiation Curing

Abstract

In the beginning of the 70ties the two types of radiation sources applied in industrial processes, electron radiation and UV, had been given rather optimistic forecasts. While UV could succeed in the field of panel and film coating, electron radiation curing seems to gain success in quite new fields of manufacturing. The listing of the suggested applications of radiation curing and a comparison of both advantages and disadvantages of this technology are followed by a number of case studies emphasizing the features of these processes and giving some examplary calculations. The data used for the calulations should provide an easy calculation of individual manufacturing costs if special production parameters, investment or energy costs are employed.

1. Introduction

It was in the late 60's that investigations had been started to transfer energy to radically polymerizable substances by using UV and electron radiation. Motivation was given by disadvantages of the available conventionally cured coating systems and by certain advantages radiation curing processes promissed to provide - we will discuss more of them later on - when hardening coatings on shaped parts of polymer material at ambient temperatures and reasonable throughputs. The experimental work had been successful at last and led to the installation of a production line, which had its start-up in 1970. Later on in 1973 and 1974 this line was followed by others in Europe carrying out the curing of varnishes upon panels of wood and particle board for furniture and doors. Meanwhile at quite a lot of sites attempts had been made to develop the appropriate materials to be cured by UV and electron radiation, and it had not been basic chemistry for coatings alone but also for adhesives, inks etc. because a number of other conventional curing processes had been found to be displaced by this new way of curing. While it was easier to move foreward in developing powerful and not too expensive UV sources, it had been those huge concrete shieldings of the convenient electron accelerators that kept potential users away from getting acquainted with this new techology, the shielding being required by the voltage of at least 350 kV powerful accelerators had been using to generate high intensity radiation in those days. A real but not even a very fast breakthrough took place, when some manufacturers of high voltage equipments made progress in developing powerful electron radiation sources based upon an acceleration voltage between 150 kV and 300 kV where the shielding of the X-rays could be provided by voltage dependent more or less thick lead plates.

There shall not be made a profound treatise of the technical details of the various types of electron sources of this voltage range which can be found easily in numerous publications, but nevertheless a short description of the different ways to generate electron radiation for an industrial scale shall be given. The so-called scanner type is the smaller brother of the medium and high voltage accelerators where the electron beam, generated by a hot cathode made of tungsten, is scanned over a certain angle within a vacuum chamber, passes through a thin window of a metal foil - usually titanium -, which serves as a barrier against the atmospheric pressure, and then is able to penetrate into substrates to start radiation chemical reactions (1,2,3). Another type provides the generating the electron radiation over the whole lenght of a filament like cathode usually positioned crosswise to the line direction. The electron current of this source is controlled by a grid. This kind of electron source is also available as a multiple filament type to achieve higher dose rates (4,5,6,7,8). A similiar way of electron generation has also been realized in the machining made by another manufacturer in a version like a module system where a number of parallel cathodes with their axis positioned along the line direction determine the width of the substrate to be irradiated (9). The last type to mention is distinguished by the electrons emerging from a cold cathode. Accelerated helium ions within a vacuum chamber strike a secondary emitter whereby each helium ion is generating a number of electrons which move in the opposite direction to pass through a window into the radiaton chamber (10,11).

Summing up, it has been the lower acceleration voltage that enabled the development of rather compact and selfshielded radiation devices which usually require not more than one meter width plus than the production line itself. Their length within the line depends upon the product type to be irradiated. Rigid panels require longer tunnels according to an effective shielding than the 1 to 1,5 m needed for the irradiation of flexible foils. As a consequence of this selfshielding design, the site remains no more a so-called restricted area where special regulations for irradiation protection have to be observed, because these irradiation sources are equipped with a very sensitive fail-safe combination of interlock safety systems, which is switching off the electron current if outside of the irradiation chamber there is to be found any radiation beyond the accepted level or if any trouble occurs e.g. the vacuum collapses or the conveyor happens to break down.

Considering the electron accelerators' voltage range from 150 to 300 kV, it depends upon the process parameters which electron penetration is found to be essential and wether to choose a source with one constant acceleration voltage or with a certain voltage range.

Usually a technical check is recommended after 1000 to 2000 operating hours to change cathodes, windows, etc. Significantly these modern radiation sources are controlled by a microprocessor which provides warnings in time and on the other hand gives hints to discover the causes of the failure rather easily. Because of this microprocessor control equipment it is generally easy to maintain and operate these electron sources by a trained person, and no specialists have to be engaged.

On the other hand according to UV sources powerful lamps and integrated radiation systems have been developed providing radiation energies up to 120 W/cm per lamp with special energy saving reflectors. Some types of UV sources are providing the radiation as pulses and furthermore it is up to the type of process wether to use the IR radiation generated by the UV lamps or not because a lot of curable systems have shown IR radiation to support the curing by UV to be essential at all (12,13,14). Thus although many pretend, UV has not really become a competitor of electron radiation but a curing method with other objects according to its possibilities. The main aspects beyond products' peculiarities and lower investment costs are the curing speed and the effective penetration. By powerful electron radiation sources reactive coating systems can be cured by some hundred meters per minute while by UV a speed of about 8 m per minute per UV lamp is available and the configuration of numerous lamps to gain higher speeds is limited by process requirements. While it causes no problems to cure coatings with a density of 120 g/m^2 by a 175 kV electron source or 380 g/m² by 300 kV with an average dose over the depth profile not less than 80 % of the surface dose it is hardly possible to cure pigmented coatings of the mentioned range by a UV source, and even with coatings of lower densities containing certain pigment types a sufficient curing is prevented. The same effect of unsufficiently cured zones may happen to occure with coatings applied upon porous substrates.

Besides the well known radically cured acrylate based coating systems increasing attention is paid to new epoxy type oligomers and monomers cured by UV due to cationic mechanism (15,16,17). Other suggestions providing better coating performances concern a dual cure by radiation polymerization and crosslinking based upon addition mechanisms which could be supported by heat (18).

Parallel to the development of these various powerful radiation sources a reasonable amount of research work has been done by chemists and process engineers too, and thus the high intensity radiation from UV as well as from electron radiation sources has proved to be an effective means to initiate polymerization in reactive systems known as radiation curing. It has been given a remarkable role among other curing processes like thermally or catalyst based, and therefore has to be considered when establishing a new line due to cure coatings, adhesives or laminates.

2) Application Examples and Features of Radiation Curing

Quite a lot of attempts and suggestions have been made to introduce this kind of radiation processing not only instead of old well established ways of manufacturing but also by creating new types of products. Not all of these attempts have gained real technological and commercial success, because to justify a change in the manner of manufacturing there must be a significant increase in the quality of the product or an obvious and not only an incremental decrease of the costs always considering the features and even more thoroughly the advantages as well as the disadvantages of this technology. But before mentioning both of them let us have a look at actually realized applications resp. at those developed at least to a pilot scale with radiation curing as a part of the manufacturing process. Radiation curing is to perform a polymerization reaction within an oligomeric or even monomeric more or less liquid material to gain a higher molweight or even a crosslinking up to a totally unsoluble polymer.

Applications:

- curing of coatings (inks and clear or pigmented varnishes)
  upon natural wood (19,20)
  plywood (21)
  particle board (22)
  laminated board (23)
  decorate foils (44)
  wrapping paper (24,34)
  polymer foils (25)
  metal substrates (26,27,28)
  metallized layers (29)
  shaped parts (30,31,32)
  optical systems (33,34)
- curing of pre-coatings of papers for metallization (35)
- curing of magnetic media (37,38)
- curing of fillers for particle board
- curing of printing inks (39,40,41,42)
- curing of antistatic coatings (43)
- curing of adhesives for foil lamination (44,45,46)
  decorate paper upon particle board.(44,23
  transfer metallization (47)
  flocks
- curing of release coatings upon various substrates (48,49,50,51)
- curing of pressure sensitive adhesives (51,52,53)

Before going into a more detailed description of some of the the above mentioned processes there will be given a short discussion of a more general listing of advantages and disadvantages, for they may give an answer to the question why, although introduced and proved in many fields, radiation curing methods are still almost unknown by a resonable number of potential users or cause a rather restrained behaviour when recommended for replacing traditional curing methods.

Of course during the last decade chemists concerned with the synthesis of conventionally curable materials and appliers of one of the above mentioned processes did made a lot of progress too, enhanced their processes in gaining a better cure response, got forward with better or completely new materials, but it depends upon the features of the special process which of the advantages is really given a decisive role.

Advantages:

- quick start up and shut down
- cold curing
- high throughput
- lower coat weight
- high quality products achievable:
    - high gloss of coatings
    - uniform surfaces
    - almost no aftercure
    - improved durability
    - abrasion resistance
    - chemical resistance
- new products available
- space saving
- saving energy
- saving natural resources
- environment saving (no solvent emissions, no flue gases)

The disadvantages of radiation curing can be derived from two main aspects: the costs for the device and the specific characteristics of radiation curable materials causing problems at some applications which can not be generally solved but have been able to be diminished in certain cases.

Disadvantages:

- high investment costs
- higner costs of radiation curable materials
- often inerting necessary
- problems concerning the application method (viscosity etc.)
- some features difficult to provide (matting)
- weak adhesion upon certain substrates
- sometimes skin irritation by the monomers
- in some cases monomer residue
- no general FDA admission for food packaging applications
- raw materials not always available for certain purposes
- radiation defects in some substrates at higher doses
- sometimes costly additional development necessary

There should be given some remarks upon the advantages which sometimes are not clearly explained in refering publications.

Especially concerning the treatment of foils the quick start and stop is optionally linked with the conveyor system resp. with the foil speed, and thus from almost tne very beginning a uniform dose is applied upon the coating.
When considering a dose range between 10 and 50 kGy, which is usually applied during curing processes, the heat generated by the radiation within a coating or a substrate is dependent on its heat capacity and is adequate to the heating of water by 2,4 K per 10 kGy.

The high throughput has to be put into correlation with the high investment costs because usually by electron processing systems high production rates can be realized and small costs per unit are only possible if the production plant is operated to a great extent. Lower coat weights are an effect of the line speed and the possibility to gain easier uniform surfaces even upon porous substrates caused by the instantanous curing. The high gloss of the coating is being derived from the types of radiation curable coatings, their lack of solvents etc. but on the other hand impedes the formulation of mat coatings. High gloss and a uniform surface are important facts in the manufacturing of floppy disks where with the conventional process a burnishing step has been unavoidable. With electron radiation curing aftercure takes place only to a rather low extent and can be neglected. Substrates with radiation cured coatings or adhesives usually can be rolled or stacked and shipped right away. UV-cured coatings usually are said to be submitted to some aftercure reactions which in fact do not really impede the handling of the products.

Durability and resistance are a matter of the type and of the completeness of the curing reaction of the radiation curable material. A comparison of the thermal stability of an acrylic system showed radiation curing to rank first, followed by UV and thermal curing (54). The saving of space is a consequence of the size of radiation curing equipment especially in comparison with thermal curing facilities, cooling zones etc. But some space outside of the curing line for the transformer, inerting facilities etc. also have to be considered.

Saving energy has been a main argument for radiation curing some time ago. It has not lost its importance but there have been developed conventionally curable materials which provide an energy saving curing reaction too. A more severe argument is given by the fact that in many places regulations concerning solvent and combustion gas emissions become effective which sooner or later according to the age of the plant will affect all coaters (55). It is proven that organic compounds like pure hydrocarbons, solvents etc. being emitted into the atmosphere can be considered as precursors of photochemical air pollutants which are believed to be together with NO_x one of the causes for growth damages of plants. Those organic compounds deriving from the application and curing of coatings as well as from washing processes within the coating and coating manufacturing industries come to the half of that emitted by the cars. In the FRG alone it is estimated to reach an amount of 350.000 tons per year (57).

Some countries have proclaimed or have decided to proclaim regulations that the amount of those organic compounds usually used in coatings to be released into the atmosphere must not be more than 100 or 150 mg/m^3, an amount that is depending on the solvent type, but nevertheless the release of organic compounds accounted as mg carbon should not exceed 50 mg/m^3. There are some technical solutions to match these regulations, one of which is the incineration of the solvents. But as the past has shown there does not always exist an adequate request for that amount of thermal energy produced by such a device. The loading of the air used for drying processes must not exceed one third of the lower explosion limit, and in fact usually it is not more than 1 to 4 g/m^3. To reach the desired incineration temperatur of about 970 K an amount of about 3,4 kg heavy oil is needed per kg solvent, provided that the load with solvent has an average value of 2 g/m^3 and an effective heat exchanger is used. If there exists a request for that heat and the whole energy system of the plant is flexible enough this should not cause severe problems but e.g. concerning the coating of furniture there is no request for that amount of heat.

Concerning the disadvantages of radiation curing methods the high costs as mentioned before are closely related with the throughput of the line. Higher costs of radiation curable material compared to conventional products are usually connected with a better performance of the coatings or adhesives etc. but there is not always a destinct demand for those better characteristics of radiation cured products. Although there is rising hope for developing radiation curable coating materials or systems the curing of which is not inhibited by oxygen. Cured in air some µm of the surface of most of the available coating systems remain tacky. Even when the surface gets tackfree by a higher dose its general performance concerning hardness, resistance etc. is worse compared to the curing in an atmosphere containing less than 500 or 1000 ppm oxygen a value ususally being recommended by the supplier or indicated by preceding investigations. With UV this problem isn't that serious although it also exists at a certain degree, but because of the slower hardening reaction this effect can be overcome by higher additions of the initiator.

Using solvent- or water-based systems it is rather easy to achieve changes concerning the viscosity by the addition of solvents because they are evaporated during the thermal curing process and are just a matter of cost. Because of the lack of volatile solvents in radiation curable products these systems are carefully formulated by the manufacturer and usually require no further improvements by the coater. If necessary the viscosity can finally be adjusted by the addition of reactive diluents also known as monomers like (meth)acrylic esters, vinyl compounds etc. They are copolymerized during the curing reaction and therefore they determine not only the final performance of the cured product but are also influencing the cure response of the coating material and thus they may affect the throughput thoroughly.

Some features more or less easily available with thermally cured products cause some problems to the formulator, like matting . Because no evaporation of solvents takes place and because the particles of matting agents are well enclosed by the coating system rather high additions are necessary to gain mat surfaces, which usually influences other properties too (58,59). Another problem that has to to be faced is its bad adhesion upon certain substrates, among which the finishing of metal substrates has been a rather inhibiting factor in the expansion of radiation curing methods. Meanwhile some problems have been solved by primers or by a pretreatment of the metal surface.

Another fact that caused some problems, when radiation curing devices were installed at already existing coating lines instead of conventional ovens, has been the skin irritancy of most of the monomers used in radiation curable formulations which happens to occur when the time for the interaction with human skin has been too long or no immediate cleaning was following the skin contact. A solution to this has been the development of less irritant compounds and a better instructions of the staff by the technical supervisor and by the supplier (60,61,62,63).

A residue of monomers after the curing reaction which has often been used as a reproach against radiation curing systems predominantly concerning recommendations for food packaging. An insufficient curing reaction is a characteristic of the individual system and should be able to be overcome. In the application case of food packaging it is not only the residue of double-bond containing crosslinkable monomers or oligomers but above all unreacted raw material or by-products left by the oligomer synthesis which should affect the methods of synthesis to meet the demands of corresponding FDA regulations.

For special applications it has been learned that it is not common to apply any available curing system that has been successful in a similiar process. Because of the special design of coatings or adhesives it is often necessary to develop new materials or even new types of products with completely different features than provided by those already on the market.

Polymer substances like foils, fibers etc. sometimes undergo radiation damages like depolymerization or elimination reactions as a by-effect of the radiation within the substrate to be laminated or coated. The so-called minimum dose for a sufficient curing reaction of the radiation curable material gives a hint to the applicability of these products upon certain substrates because the radiation stability of the different types of polymers used in existing production lines is well known by many investigations. Modern radiation curable products are designed to meet a higher cure response and therefore need doses below these critical values.

While systems curable by electron radiation as well as by UV may be based upon the same oligomers care must be taken of the shorter pot life of already initiated UV systems which might be polymerized within the application device.

As a negative effect of the already above mentioned disadvantages like a lack of availability of well designed raw materials for new applications many potential users are prevented to get into a firmer contact with this technology. Concerning new processes it has been learned that a lot of costly investigation work has to precede before sufficient results justify the installation of a curing line. Although the opinion is widespread that the development work is already financed by the bill for the coating material both supplier and user should agree with sharing the risk in those cases.

3. Technical and Economical Comparison of Conventional and Radiation Curing Processes:

A technical and economical treatise on typical applications of radiaton curing processes should give an illustrative overview how the integration in production lines is managed technically and which costs have to be faced when choosing radiation curing methods. The cost comparison doesn't include devices which are assumed not to be dependent on the kind of curing. Because the costs concerning space differ widely according to where the plant is sited, there should be mentioned that e.g. in central Europe for industrial buildings an investment of about US$ 350,-/m^2 has to be taken into account.

The way numerical data are presented should provide an easy modification of the given calculation by the reader according to different local costs for energy, water etc. or even according to investment costs. According to the production of thermal energy necessary for a curing line a dissipation among other consumers within a firm can make a process more reasonable, but this can hardly be taken into account here.

For the calculation of operating costs the following charges are assumed:

electric energy	0,086	US$/kWh
heavy oil	0,164	US$/kg
natural gas	0,16	US$/m^3

The cost for circulating cooling water by a refrigerating system to preserve natural or public fresh water supplies is assumed to be:

cooling water	0,291	kWh$_{el.}$/m^3.K

Nitrogen is provided in liquid form and stored in an insulated tank. Depending on the consumption of nitrogen per year and on the contract of delivery a rent of about 12.000,- US$/a for the tank has to be taken into account especially if the amounts needed are as small as discussed here. The charge for liquid nitrogen may vary according to the location of the curing line and therefore the data used here should be regarded as an example and must be adapted according to local conditions.

nitrogen charge 0,30 US$/$m^3$

According to the capital costs the local interests for the annuity may be different. For the examples below the interests are assumed to be 8 % .

3.1. Panel coating:

According to type of product the way to apply and to cure coatings differs widely. Panels for furniture e.g. with veneer surfaces undergo a lot of finishing steps. At first the surface is sanded, grounded with a water-borne primer, thermally cured, stained with a solvent-based system, ground coated by casting or by a roll (1 or 2 times) and cured by air-convection, IR or UV. The application of the base layers is followed again by sanding and staining, and at last one or two layers of the clear top varnish are applied by casting rolling or by spraying. The curing may be carried out thermally or by radiation. On the other hand there shall be reviewed a coating line for a particle board used for furniture or as a door panel the surface of which usually undergoes one or two times sanding and being coated with filler, sanded again and topcoated with a pigmented coating.

A case comparison of the curing parameters of the clear top varnish by three versions of curing lines shows the energy requirement of the topcoat and gives hints to find out which type is matching the manufacturing assumptions best. The investment sum includes merely the curing tunnel or chamber and additional devices mentioned below but no other parts of the plant like coaters, conveyors etc.

In the conventional way the varnish upon the veneer is cured thermally by an infrared dryer or by air convection heated by a gas/oil-fired burner.

Although at the same coefficient of utilization the different line speeds would run into individual throughputs, for comparative reasons a uniform number of 2000 operating hours and a uniform surface of 1 million square meters are assumed.

Uniform manufacturing assumptions:

coating surface:	1,000.000	m^2/a
operating hours:	2.000	h/a
coating weight(dry):	min. 40	g/m^2

Case A: <u>Veneer Coating Thermally Cured</u>

The curing is performed in a tunnel purged by heated air, and the energy is provided by an oil-fired burner. With the data below an effectivity of 56 % at 1 m width is assumed.

curing conditions: 2 min at 15 m/min at 373 K

drying air: solvent content: max. 2 g/m^3
total volume per year: 90.10^6 m^3

heavy oil consumption: 358 t per year

coating: clear varnish, acid catalyzed type, 65 % solvent, applied by casting

application quantity:	115	g/m^2
cost	2,80	US$/kg
total amount	115	t/a
total varnish cost	322.000,-	US$/a

solvents: for cleaning and deluting purposes

cost	1,-	US$/kg
total amount	26	t/a
total solvent cost	26.000,-	US$/a

total material costs: 348.000,- US$/a

According to the above mentioned regulations no solvent loaded air deriving from the drying tunnel should be released into the atmosphere, and thus there are made three suggestions for the solvents' disposal:

a) <u>Incineration:</u>

Integrated incineration devices are available for certain maximum air throughputs, e.g. for 35.000 m^3/h. The heat of the gas-fired burner is usually provided by a reverberatory flame consuming about 400 to 500 m^3/h of natural gas. The solvent is incinerated at 973 K, heat recuperation can be performed by using a heat exchanger at 770 K. Because this facility requires more energy than the curing process itself there is no additional fuel taken into account for the curing. The investment costs are including the integrated incineration device.

investment:	1,200.000,-	US$
operating requirements:		
el. power	60	kW
natural gas	660.000	m^3/a

calculation case Aa:

capital costs (10a)	178.835,-	US$/a
maintenance (5 %)	60.000,-	US$/a
varnish + solv.	348.000,-	US$/a
el. energy	5.160,-	US$/a
natural gas	105.600,-	US$/a
total costs	697.595,-	US$/a

costs per sqm 0,698 US$/$m^2$

b) Activ Carbon Adsorption:

The solvent is adsorbed at active carbon and two adsorber columns have to be operated at the same time because the steam cleaning of the full column must be guaranteed during the curing process. Solvents containing ketones will cause difficulties for their molecular disintegration at the operating temperatures might bring about the inflammation of the carbon. Some additional problems may derive from the disposal of the solvent containing water after condensation and phase separation. This last aspect might contribute to the calculation as well but has not been dealt with here (65).

A plant for the above described coating line would require the following consumptions. Usually 4 kg steam are needed per kg solvent, about 30 m^3 cooling water per hour and an electric power of about 40 kW is required. The carbon consumption is about 1,6 kg per t solvent.

investment: 1,350.000,- US$

operating requirements:

el. power:	80	kW
heavy oil:	358	t/a
cooling water:	60.000	m^3/a

calculation case Ab:

capital costs (10a)	201.190,-	US$/a
maintenance (5 %)	67.500,-	US$/a
varnish + solv.	348.000,-	US$/a
el. energy	13.760,-	US$/a
heavy oil	58.712,-	US$/a
cooling water	15.016,-	US$/a
total costs	704.178,-	US$/a

costs per sqm 0,704 US$/m^2

c) Drying by Nitrogen:

Nitrogen as the drying medium is avoiding any problems concerning environment and explosion limits because the absence of oxygen allows the loading up to a solvent dependent saturation limit. In this particular application case a maximum load of 400 g/m^2 has been assumed. The part of the tunnel the solvent is evaporated has to be designed gas tight, and the nitrogen is circulated within a cooling and a heating system. The solvents are condensed by cooling and the nitrogen is heated up for the next drying step (66).

Because of the recuperation of the solvent no expenses for additional solvents must be taken into account.

investment: 460.000,- US$

operating requirements:

el. power	30	kW
heavy oil	3,0	t/a
nitrogen	110.000	m^3/a
cooling water	2	m^3/h

calculation case Ac:

capital costs (10a)	68.554,-	US$/a
nitrogen tank	12.000,-	US$/a
maintenance (5 %)	17.500,-	US$/a
varnish	322.000,-	US$/a
el. energy	5.160,-	US$/a
heavy oil	492,-	US$/a
nitrogen	33.000,-	US$/a
cooling water	1.001,-	US$/a
total costs	459.707,-	US$/a

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*                                          *
*  costs per sqm           0,460   US$/m²  *
*                                          *
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Case 5: Veneer Coating Cured by UV Radiation

The clear top varnish is cured by UV radiation. For the reasons of protection from UV-radiation and ozone generated by it the curing is performed within a tunnel at an average speed of 8 m/min per lamp according to the reactivity of the varnish. The number of lamps is limited by operating and reactivity parameters, e.g. an effective cooling must be provided and a perfect surface optained. The varnish is an acrylate based type without evaporating solvents. The higher speed of the UV-curing line provides larger throughputs, but for the reason of an easier comparison the same coating surface is assumed. For varying calculations the concerning data could easily be exchanged. For the same reason the operating hours per year have been left at 2000 h/a, and therefore a smaller utilization coefficient is resulting. On the other hand too many breaks shorten the life time of the lamps, 1000 to 2000 hours per lamp are common. That is the reason why at some lines the UV lamps are not switched off during curing intermissions, a fact that has not been taken into account in the calculation below. The consumption of el. energy also includes the fans for cooling and exhausting, the latter providing a capacity of about 3000 m³/h.

curing speed:		25	m/min
coating:	100 % solid UV curable clear varnish, applied by a roller coater		
	application quantity:	45	g/m²
	cost	6,80	US$/kg
	total amount	45	t/a
	total cost	306.000,-	US$/a
solvents for cleaning:			
	cost	1,-	US$/kg
	total amount	2	t/a
	total cost	2.000,-	US$/a
total material costs:		308.000,-	US$/a
	Investment:	40.000,-	US$
	Operation requirements:		
	el. power	55	kW

calculation case B:

capital costs (10a)	5.961,-	US$/a
maintenance (5 %)	2.000,-	US$/a
UV lamps	1.080,-	US$/a
varnish + solv.	308.000,-	US$/a
el. energy	9.460,-	US$/a
total costs	326.501,-	US$/a

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*                                          *
*  costs per sqm          0,327   US$/m²   *
*                                          *
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Case C: Veneer Coating Cured by Electron Radiation

The main features of curing by electron radiation have been described above, and there should only be mentioned that for this case the pricipal need for inertization has been assumed although it has been reported that the creation of some coating systems curable in air had been successful at last. To provide an inert atmosphere within the curing chamber is a cost-determining factor, and thus two possibilties are given for the calculation. According to the square meters coated per year EB-curing is able to cure a multiple area of the 1,000.000,- m^2/a, and therefore the calculation is performed for a greater throughput too. Electron radiation sources of almost every type can be equipped with distinct window widths between 25 and 240 cm according to the curing purpose. For the following example a width of 130 cm is assumed. The width of the whole source within the line usually will not exceed 230 cm, the shielded tunnel for the coating of 2 m panels would require a length of about 10 m. For cooling the window of the electron source cooling water must be provided. The electric power also includes the fan for exhausting the radiation chamber.

Electron sources are available at different powers thus offering distinct dose rates and cure speeds. For this application, which need not guarantee a high velocity curing, a electron source type providing a dose-speed-product of 3000 kGy.m/min is selected. Assuming a curing dose of 30 kGy which seems to be no problem at all for this type of coating a line speed of 100 m/min could be realized. If panels of 1 m width are coated and a coefficient of performance of 70 % is assumed a throughput of 4.200 m^2/h can be gained. In contrary the investment costs do include the shielded conveyor.

electron radiation source:

acceleration voltage	175	kV
current	135	mA
window width	135	cm
dose-speed-product	3000	$kGy.m.min^{-1}$

curing speed: 50 m/min

coating: 100 % solid electron radiation curable clear var
applied by a roller coater

curing dose	min.	30	kGy
application quantity:		45	g/m^2
cost		6,20	US$/kg
total amount		45	t/a
total varnish cost		279.000,-	US$/a

solvents for cleaning:

cost	1,-	US$/kg
total amount	2	t/a
total cost	2.000,-	US$/a

total material costs: 281.000,- US$/a

investment: 1,000.000,- US$

operation requirements:

el. power	50	kW
cooling water	2,5	m^3/h
inert gas	150	m^3/h

a) Inert Gas by Gas/Oil Combustion:

Inert gas can be generated by the combustion of oil, natural gas or propane by special generators by which an oxygen level as much as 100 ppm or less cannot be gained easily (67,68). For those applications requiring a lower oxygen level a catalytic treatment of the gaseous combustion products is necessary to reduce the oxygen content. The following table presents some data concerning costs and amounts to gain 100 m^3 inert gas at standard conditions. Of course the costs must be considered to be average rates. For the calculation below heavy oil was taken as fuel. Using natural gas and especially propane would increase the costs for inerting. But it should be easy to modify the calculation by exchanging the concerning data.

fuel	amount/100 m^3	costs/100 m^3 US$
heavy oil	9,5 kg	1,56
natural gas	11,7 m^3	1,97
propane	4,6 m^3	4,90

Inert gas generators are available with various outputs. The data of two sizes are given below.

inert gas generators:

output rate m^3/min	el. power kW	cooling water m^3/h	investment US$
100	18	7,5	72.000,-
300	45	22,5	100.000,-

calculation case Ca:

For both the electron source and the inert gas generator an amortization period of 10 years is assumed.

capital costs (10a)	163.932,-	US$/a
replacements	2.429,-	US$/a
varnish + solv.	281.000,-	US$/a
el. energy	13.760,-	US$/a
cooling water	8.759,-	US$/a
heavy oil for inerting	4.680,-	US$/a
total costs	474.560,-	US$/a

costs per sqm 0,475 US$/$m^2$

b) Liquid Nitrogen:

Another method to provide an inert gas atmosphere is purging the radiation chamber with pure nitrogen usually delivered to the coating site in liquid form and thus kept in an insulated tank (66).

calculation case Cb:

capital costs	149.029,-	US$/a
nitrogen tank	12.000,-	US$/a
replacements	2.429,-	US$/a
varnish + solv.	281.000,-	US$/a
el. energy	10.320,-	US$/a
cooling water	1.251,-	US$/a
nitrogen	90.000,-	US$/a
total costs	546.029,-	US$/a

```
****************************************
*                                      *
*  costs per sqm          0,546  US$/m²*
*                                      *
****************************************
```

Classified according to the costs per m², case B goes first followed by the cases Ac, Ca, Cb, Aa and Ab, which means that according to the assumptions made above UV seems to be the most economic curing method for this special application.

Which curing method is most economical at varying manufacturing assumptions like a certain output rate and under which environmental circumstances must be a matter of a more comprehensive calculation even if the main task is the same as in the cases A to C ? Special items that have not been taken into account for space requirements and labour costs have proved to be misleading in former calculations because modern thermal curing systems for panels like the vertical lift dryer are requiring less space than older drying tunnels and furthermore provide a rather economical treatment of the drying air by separated drying zones and an optimum heat recuperation.

Assuming 2 million square meters per year and 3000 hours for operating the thermal curing line the costs per square meter would naturally decrease and the costs for the varnish itself become more important.

Case	$A=1.10^6$ m²/a US$/m²	$A=2.10^6$ m²/a US$/m²
Aa	0,698	0,566
Ab	0,704	0,565
Ac	0,460	0,405
B	0,327	0,317
Ca	0,475	0,379
Cb	0,546	0,414

As the data show a rather significant reduction in costs is performed by the greater production rate except for the method B (UV). A more precise comparison considering the higher labour costs for the thermal curing, according to the 3000 h/a, may shift the economic benefits from case Ac to the radiation curing method Cb, whereas the reduction of the costs per m² is strongly influenced by the part of the capital costs and the possible maximum output which in the cases Ca and Cb could reach 3.10^6 m²/a at the rather generous utilization coefficient of 50 %.

As a cheaper substitute of natural veneers or high pressure laminates panels for furniture or doors can be manufactured of particle boards coated with pigmented varnishes. Particle boards are usually coated with a UV curable filler, sanded and coated with 90 to 120 or more g/m² of a pigmented coating. Because of the application quantity and the pigment concentration the curing is performed by heat or electron radiation.

For the calculation the following assumptions are made:

coating surface	1,000.000	m²/a
operating hours	2.000	h/a
coating weight (dry)	min. 100	g/m²

Case Da: Pigmented Coating Thermally Cured with Integrated Solvent Incineration

curing conditions: various curing zones at different temperatures starting with 323 K, the highest being 413 K
the length of the tunnel at least 150 m

line speed	20	m/min

drying air:

solvent content:	maximum	4	g/m^3
	average	2	g/m^3
total volume per year:		$50 \cdot 10^6$	m^3/a

coating: pigmented varnish, acid catalyzed type, 40 % solvent, applied by casting

application quantity:	180	g/m^2
cost	2,50	US$/kg
total amount	200	t/a
total coating cost	500.000,-	US$/a

solvents: for cleaning and deluting purposes

cost	1,-	US$/kg
total amount	20	t/a
total solvent cost	20.000,-	US$/a

total material costs:	520.000,-	US$/a
investment:	1,750.000,-	US$

operating requirements:

el. power	100	kW
natural gas	1,320.000	m^3/a

calculation case Da:

capital costs	260.802,-	US$/a
maintenance (5 %)	87.500,-	US$/a
varnish + solv.	520.000,-	US$/a
el. energy	17.200,-	US$/a
natural gas	211.200,-	US$/a
total costs	1,096.702,-	US$/a

```
*******************************************
*                                         *
*   costs per sqm          1,097  US$/m²  *
*                                         *
*******************************************
```

Case Db: Pigmented Coating Cured by Electron Radiation

The different features of the electron processing system are not repeated here. Because of the high dose-speed-product a similiar electron source can be employed, inerting is provided by an oil-fired generator. Because of the handling of the panels no higher speeds than 50 m/min seem to be useful. The investment costs are including the shielded conveyor and the inert gas generator.

acceleration voltage	200	kV
current	140	mA
window width	140	cm
dose-speed-product	3000	kGy.m.min^{-1}

curing speed: 50 m/min

coating: 100 % solid electron radiation curable pigmented varnish, applied by a roller coater

curing dose	min.	40	kGy
application quantity:		110	g/m^2
cost		6,40	US$/kg
total amount		110	t/a
total varnish cost		704.000,-	US$/a

solvents for cleaning:

cost	1,-	US$/kg
total amount	2	t/a
total solvent cost	2.000,-	US$/a

total material costs:	706.000,-	US$/a
investment:	1,100.000,-	US$

operation requirements:

el. power	50	kW
cooling water	2,5	m^3/h
inert gas	150	m^3/h

calculation case Db:

capital costs	163.932,-	US$/a
replacements	2.429,-	US$/a
varnish + solv.	706.000,-	US$/a
el. energy	13.760,-	US$/a
cooling water	8.759,-	US$/a
heavy oil for inerting	4.680,-	US$/a
total costs	899.560,-	US$/a

```
******************************************
*                                        *
*  costs per sqm          0,900   US$/m²   *
*
******************************************
```

Case	$A=1.10^6$ m^2/a US$/m²	$A=2.10^6$ m^2/a US$/m²
Da	1,097	0,887
Db	0,900	0,803

In these cases where the expenses for the varnish represent the main part of the manufacturing costs the radiation curing method is about 18 % in advance which is finally reduced with the greater output, but as mentioned before labour savings and according to the length of the thermal curing line space savings should play a rather important role.

3.2. Curing of Coatings upon Shaped Parts

Although this application had been the first to be realized the efforts installing it instead of existing thermal curing advices have been made slowly and in rather special fields like in the coating of rims and of petrol tanks of motor bikes. In the case of the rims a listing of data is given below. The curing is performed within chambers of a cicular shelve admitting only one single rim per chamber. After evacuating and flooding with nitrogen the curing is performed by the electron beam, the dose being high enough to provide a sufficient curing reaction at all surface elements (69).

Specifications of the electron processing system:

acceleration voltage	200	kV
electron current	40	mA

production per year	2,100.000	rims/a
radiation curing dose	250	kGy

cost factor	unit	case Ea (thermal curing)	case Eb (EB curing)
investment	US$	720.000,-	580.000,-
coating:			
quantity	g/m²	100	40
quant./rim	g	21	8
quant./a	t/a	50	20
cost	US$/kg	2,45	6,20
energy:			
operat. hours	h/a	2300	2200
el. energy	kW	127	50
nat. gas	m³/a	380.000	-
nitrogen	m³/a	-	88.000

calculation case Ea:

capital costs (10a)	107.301,-	US$/a
maintenance (5 %)	36.000,-	US$/a
varnish	122.500,-	US$/a
el. energy	25.121,-	US$/a
natural gas	60.800,-	US$/a
total costs	351.722,-	US$/a

```
********************************************
*                                          *
*   costs per rim           0,168  US$/rim *
*                                          *
********************************************
```

calculation case Eb:

capital costs (10a)	86.437,-	US$/a
nitrogen tank	12.000,-	US$/a
maintenance (5 %)	29.000,-	US$/a
varnish	124.000,-	US$/a
el. energy	9.460,-	US$/a
nitrogen	26.400,-	US$/a
total costs	287.297,-	US$/a

```
********************************************
*                                          *
*   costs per rim           0,137  US$/rim *
*                                          *
********************************************
```

According to the assumptions the curing of coatings on rims by the electron irradiation should be more cost effective.

3.3. Curing of Coatings upon Foils

Coated papers (printed or not), polymer foils, metallized surfaces etc. are used widely for laminating, packaging and insulating purposes and are manufactured from roll to roll at large quantities. Because of the very high production rates radiation curing seems to be the matter of choice, by the help of which unique - if desired supersmooth - surfaces can be gained at high speeds. Wet coatings upon compatible printing inks is no problem and the coated webs or foils can be delivered without any delay. Conventional curing lines are based upon infrared or heated air as the drying medium, coatings applied are cellulose nitrate, urethane-based, or water-borne systems. With the instant cure by electron radiation there derive no problems from the penetration into porous substrates if the viscosity of the coating system is well controlled. New developments in this field use smooth or structured drums at the coating surface's side performing the curing from the back side.

Like above operating costs of three cases are given partly taken from a foil converting line performing the curing by electron radiation.

manufacturing specifications:

coating quantity	3	g/m^2
web width	165	cm
production rate	13.000	m^2/h

For a comparison of the operating costs it is assumed that the thermal curing is provided by a gas-fired oven, the radiation equipment is a 165 cm wide electron source delivering 165 mA at 200 kV. The thermally curable varnish contains 60 % solvents. The calculations FA and Fb do not include capital costs.

Cost factor	unit	case Fa (thermal curing)	case Fb (EB curing)
Coating costs	US$/kg	3,20	7,20
nat. gas	m^3/h	25	
solv. inc.	US$/h	5	-
el. energy (curing)	kW	-	50
el. energy (fans etc.)	kW	13	5
cooling water	m^3/h	3,0	2,5
inerting	m^3/h	-	60

calculation case Fa:

varnish	312,00	US$/h
el. energy	1,12	US$/h
natural gas	13,60	US$/h
solv. inc.	5,--	US$/h
cooling water	0,75	US$/h
total costs	332,47	US$/h

```
*****************************************
*                                       *
*  costs per m²          0,0256  US$/m² *
*                                       *
*****************************************
```

calculation case Fb:

varnish	280,80	US$/h
el. energy	4,73	US$/h
inerting (comb.)	2,44	US$/h
cooling water	0,63	US$/h
total costs	288,60	US$/h

```
*****************************************
*                                       *
*  costs per m²          0,0222  US$/m² *
*                                       *
*****************************************
```

The listings show the operating costs of both the thermal and the radiation curing method to be mainly dependent upon the coating costs, a fact which recommends radiation curing for functional and decorative coatings according to the excellent performance radiation cured surfaces usually offer. Assuming investment costs of US$ 1,000.000,- in case Fb and an operating time of 2000 h/a the costs would rise by 0,0057 US$/m^2 proving that for high throughputs the costs of coatings dwarf the costs of the equipment.

3.4. Curing of Printing Inks

In contrast to conventional inks, radiation curable inks do not contain any solvents which have to be removed by thermal processes like hot air convection, gas flame heating, infrared, microwaves etc. which is also requiring more space. Radiation curing methods need of course new types of inks, sometimes an alteration of the printing process and in some cases like offset printing because of the behaviour of the acrylates special formulations have to be created not to interfere with the water. With radiation curing printing can be done more beautiful than with flexo, printing and top coating can be performed in line, less expensive substrates can be used, and the printings and coatings are scratch resistant right away.

For comparative reasons the data below show some cost factors of both a conventional and a thermal curing line.

cost factor	unit	conventional curing	radiation curing
ink costs	US$/kg	4,50-8,00	8,00-12.00
line speed	m/min	150	500
curing energy	kWh/1000 m^2	17	5

Below there is given a set of data for calculating the operating costs of an electron source used for offset printing line.

electron source specifications:

acceleration voltage	175	kV
electron current	300	mA
width	100	cm
dose-speed-product	9000	kGy.m.min^{-1}
line speed	200-300	m/min

investment:

electron source	900.000,- US$
inert gas generator	75.000,- US$

operating requirements:

el. power	80	kW
cooling water	7	m^3/h
inerting	80	m^3/h
replacements	1,50	US$/h

calculation case G

For the calculation 2000 operating hours per year and an average production rate of 15.000,- m^2/h are assumed. As above the requirements of the inerting are included.

capital costs	145.304,-	US$/a
replacements	3.000,-	US$/a
el. energy	16.856,-	US$/a
cooling water	7.258,-	US$/a
gas for inerting	3.744,-	US$/a
total costs	176.162,-	US$/a

```
*****************************************
*                                       *
*  costs per 1000 m²     5,87  US$/1000 m²  *
*                                       *
*****************************************
```

If nitrogen is used instead of combustion gas for the inerting total costs of 225.568,- US$/a have to be considered giving 7,52 US$/1000 m^2...

3.5. Silicon Release Coating

Silicon release layers between 0,4 and 1,5 g/m^2 are common for a wide range of products like caul stock, tapes etc. Usually release-coated products are manufactured at high output rates of some million square meters per year at line speeds between 160 and 300 m/min. New regulations against air pullution and restrictions concerning the consumption of natural energy resources like oil and gas force the former solvent based and emulsion type release coatings to give way to 100 % solid type coatings. On the other hand thermal curing steps usually require rehumidification of paper-like substrates or are not applicable at all if coatings upon thermal sensitive substrates like polyethylene have to be cured. The table below gives an overview of the different silicon release coatings and their particular energy requirements. The data are refering to a silicon coating line providing an application quantity of 0,8 g/m^2 upon a 1,5 m wide foil at a speed of 165 m/min. Solvent-based systems usually contain 90 to 95 % solvent. Earlier some hesitation in accepting the radiation curing technology had been derived from the availability of the radiation curable silicon material providing a wider range of separation characteristics.

Recently development work had also been sucessful in the finding of radiation curable adhesives providing the production of release and adhesive layers within the same device operating one or two accelerators in line.

Si-release system	energy consumption kJ/m^2	costs US$/kg
solvent based		(dry) 11,90
+ solv. recovery	352	
+ solv. incineration	240	
emulsion type	267	
100 % solid, therm. cured	212	17,90
100 % solid, UV cured	140	19.60
100 % solid, EB cured	42	23.60

The table is merely considering the energy for the curing reaction and is not paying any attention to other expenses like rehumidification for paper substrates or inerting the radiation curing zone.

The listing below presents some operating data of a silicon release coating line, but according to the features of porous and thermally sensible substrates there are limitations to be faced when operating the thermal or the UV curing line.

production speed	200	m/min
substrate width	120	cm
production rate	14.000	m^2/h

operating data	units	thermal	UV	EB
coating costs	US$	11,90	19,60	23,60
el. energy (dryer)	kW	770	44	45
el. energy (fans, etc.)	kW	230	5	5
steam for rehumid.	kg	100	-	-
cooling water	m^3/h	0,5	-	2,5
inerting	m^3/h	-	-	100

3.6. Curing Adhesives for Laminating

Flexible laminates are used as packaging or decorative material consisting of two, three or more layers which by modern machinery can be laminated together in one step from roll to roll. Like coated foils, due to the high output rates laminates should be a preferred field for radiation curing. Special developments called "transfer methods" offer the laminating of already cured varnishes or metallic layers onto foils by curable adhesives. By a special design of the plant it should be possible to cure a top coat and the laminating adhesive at the same curing step. Before any decision about the curing method special attention has to be paid to the type of substrate and to the availability of highly reactive adhesives according to radiation damages of one of the substrates.

Modern conventional adhesives for laminating are water-borne or high solid material like one or two component urethane-based systems. For application (viscosity) reasons an amount of 1 to 3 g/m^2 is applied at higher temperatures. The rather slow curing reaction of these systems force the manufacturers to store the laminated rolls for 5 to 8 days for final examinations before being delivered to the customers. Laminates made with radiation curable adhesives allow an instant further processing and do not require any storage before delivery as well as rejects are almost non existent. Because of their highly crosslinked structure heat sealing is of course provided.

Laminating of a decor foil upon a rigid board and the curing of the top coat in one step have been succesfully executed years ago and seem to be an interesting version of laminated board. Another development provides the curing of two or more impregnated layers of paper to form a laminate or to be laminated to a board, the curable system in case being the adhesive as well as the top coat.

Calculations can be easily derived from the above mentioned converting of foils. Radiation curable adhesives require curing doses of about 20 kGy and the line speed is merely a matter of substrate handling. In contrast to foil coating, inerting seems to be no cost factor at all, but for corrosion inhibition the radiation chamber can be purged with a small amount of nitrogen.

The following table provides some data for comparative reasons.

Cost factors	unit	conventional	radiation
		curing	
adhesive	US$/kg	5,70	8,30
line speed	m/min	150-300	150-800
product storage	days	5-8	0
cooling required		yes	no
FDA admission		yes	attainable

3.7. Curing of Magnetic Media

One of the just emerging techniques in this field is the curing of magnetic media because it is active on a rapidly growing market and there is no saturation to be seen in near future. For the time being megnetic tapes and disks are the most important media for a permanent storage of information in computer industries.

One of these plants using electron radiation is manufacturing floppy disks. The substrate of these floppy disks is a 76 µm thick polyester film which is coated on both sides with a thin layer of magnetic pigment and organic binder ranging between 1 µm and 100 µm. Conventional magnetic coatings contain 65 % solvents, which after drying leave a magnetic layer consisting of about 60 % magnetic pigment and 20 % binder resin, the rest being fillers, additives etc. The conventional thermal curing is a rather complex process comprising magnetizing the coated web in a magnetic field for random orientation, drying of the urethane-based binder by hot air, calendering, storing for for several days to run the curing reaction to completion and burnishing the punched disk before testing and selling.

By the radiation curing facility a 508 mm wide polyester web is coated with a magnetic layer at a speed of 150 m/min, and although for reasons of application the coating contains 65 % solvent the manufacturing offers a great deal of technical and economical benfits. The plant works almost fully automated, the coatings are thoroughly cured, less burnishing is required, the liquid coatings cause no problems according to their stability and less space is occupied. The expensive solvent is almost totally recovered. The curing is performed by the electron source specified below, the costs of the curing equipment being about 10 % of the total costs:

acceleration voltage	250	kV
current	260	mA
window width	50,8	cm
dose-speed-product	15.000	$kGy.m.min^{-1}$
investment	500.000,-	US$
inerting	20.000,-	US$/a

This particular example of electron curing as a part of a modern production plant is a rather typical one indicating which cost factors bring about a certain technology to go ahead. In spite of evaporating solvents the omission of storage costs, less burnishing and almost no rejects have been discovered to be those benefits which could not be forseen at all to become the main reasons of a commercial success.

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