Synthetic and metal organic photochemistry in industry

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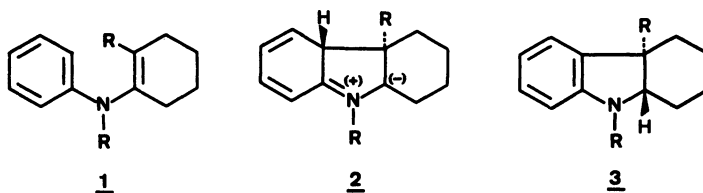
Abstract - Photochemical production processes are still extremely rare. With three examples from our own research laboratories illustration is made, how the acceptance of photochemical methodology can be increased. A diastereoselective photocyclisation and two newly designed organometallic photoinitiators succeeded because they overcome drawbacks of conventional operations.

INTRODUCTION

G. Ciamician (ref. 1), the father of photochemistry, predicted in a lecture before the International Congress of Applied Chemistry in New York as early as 1912:
"I do not believe, however, that the industry should wait any longer before taking advantage of the chemical effects produced by light." This vision has not come true and large photochemical production processes are still extremely rare. Since there are a number of reviews on industrial photochemistry (ref. 2-4) we would like to concentrate on how the acceptance of photochemical methodology can be increased. Photochemical processes in synthesis, especially those with a quantum yield of less than unity are often looked on with suspicion by our colleagues from the developement or production departements. But if the photochemical approach can overcome certain drawbacks of conventional operations the acceptance will be considerably increased. We would like to show with three examples from our own research laboratories, that there are chances for photochemistry in organic synthesis and organometallic chemistry.
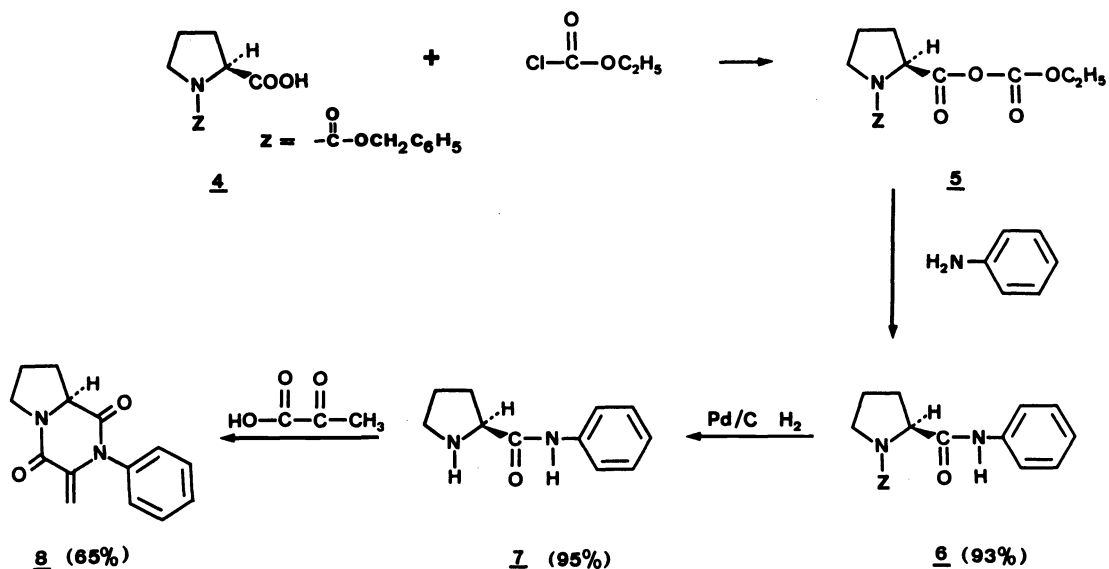
S-2-INDOLINE CARBOXYLIC ACID

S-2-Indoline carboxylic acid (10) is a key intermediate for a number of pharmaceuticals (ref. 5). The conventional synthesis includes a resolution of the racemic mixture of the amino acid (ref. 5,6). We have designed a diastereoselective photochemical approach to synthesize enantiomerically pure S-2-indoline carboxylic acid (ref. 7). The key step of the synthesis is a diastereoselective photocyclisation of an enamine moiety.
Diastereoselective photocyclisations are scarcely known in the literature (ref. 8). There have been a few attempts to carry out such reactions, but to date the diastereoselectivity is rather low (ref. 9-11).
Enamine cyclisations, however, yielding indoline derivatives, have been studied by a number of groups (ref. 12-16). Grellmann and coworkers have intensively studied the mechanism of this type of reaction (ref. 17-19).
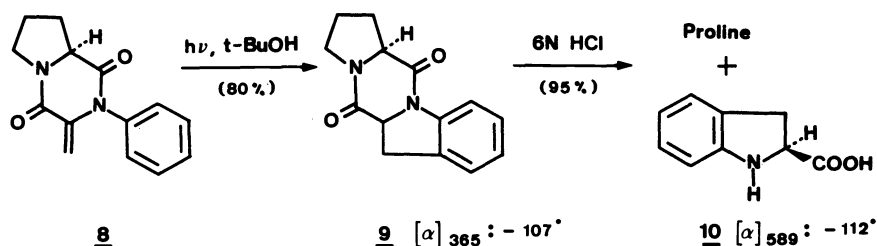

They showed that a 1,4-sigmatropic shift from the zwitterionic intermediate (2) led to the product (3).

Our objective was to make use of this well studied reaction by introducing a chiral auxiliary into the substrate and then make the substrate rigid enough to facilitate the transfer of the chiral information. This aim was reached by preparing a diketopiperazine (8) with proline as the chiral auxiliary.
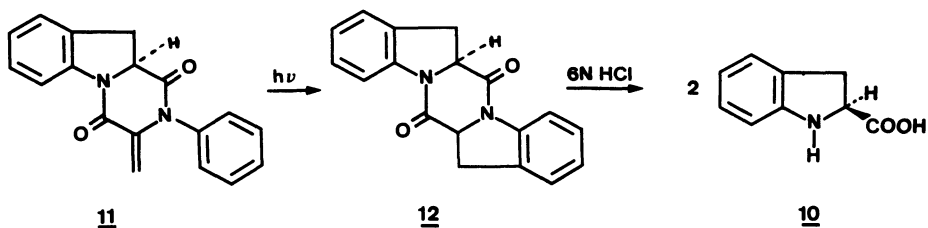
The diastereoselectivity of the subsequent photocyclisation (8) → (9) proved to be greater than 95 %. The purity of cyclisation product (9) was established by chromatography on a tri-acetylcellulose column (ref. 20) and the enantiomeric purity of the S-2-indoline carboxylic acid (10) was - after hydrolysis and workup - measured by its optical rotation.

The yield of the photoreaction proved to be dependent on the solvent used. Whereas in benzene solution the conversion reached only about 25 %, t-butanol proved to be the best solvent for this photocyclisation. Complete conversion and an isolated yield of 80 % of (9) was thus reached.

This process is satisfactory, however, a minor drawback is the separation of proline from (10) after hydrolysis and the recycling of the chiral auxiliary. To overcome this we used S-2-indoline carboxylic acid as a chiral auxiliary and thus tried to achieve chiral prolifer-ation. The exomethylene diketopiperazine substrate (11) was synthesized analogous to the pre-paration of (8) and the photocyclisation worked well to yield the S-2-indoline carboxylic acid dimer (12).

After hydrolysing (12) a separation is now unnecessary.

All in all we have a photochemical approach for the manufacture of S-2-indoline carboxylic acid which starts with a rather cheap chiral auxiliary and utilizing aniline and pyruvic acid, both bulk chemicals, and a photochemical key step in the synthesis.

To our knowledge this is the first photocyclisation reaction giving rise to a diastereo-selectivity of greater than 95 %. It is a feasible alternative for the manufacture of S-2-indoline carboxylic acid.
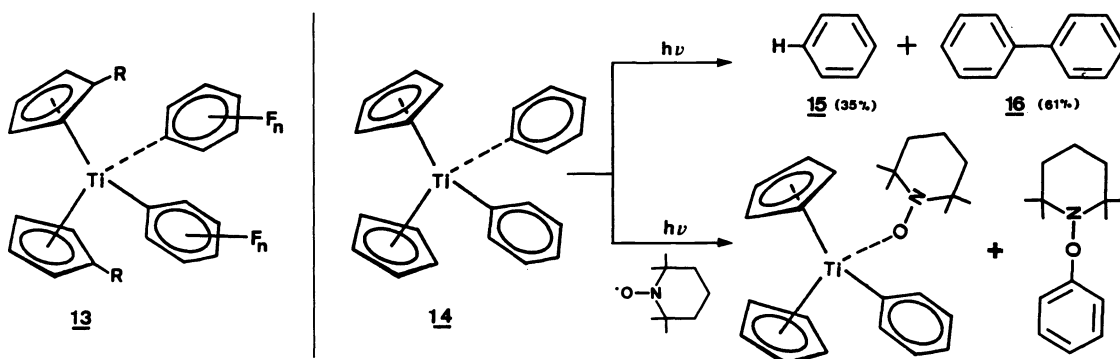
TITANOCENE PHOTOINITIATORS

One of the most prominent user of photochemistry in industry is the polymer chemist. Photopolymerisation plays a dominant role in the manufacture of integrated circuits (ref. 21). At present the predominant approach to photopolymerisation is by means of light induced free radical initiation of suitable monomers (ref. 22).
For a number of years various groups have tried to develop photoinitiators for this process that allow manufacture of permanent coatings and insulating layers in the thickness range required in integrated circuit manufacture to serve as a planarizing dielectric between metal layers. However, all of the systems developed suffer from one of the following shortcomings: poor shelf-life, poor photospeed, limitation to very thin layers.
We have been working with organometallic species with high thermal stability which readily decompose upon irradiation.
During this work we have found photosensitizers based on titanocene structures, that meet these requirements and are furthermore the first sensitizers that allow the production of photostructures of up to 70 µm thickness (ref. 23).
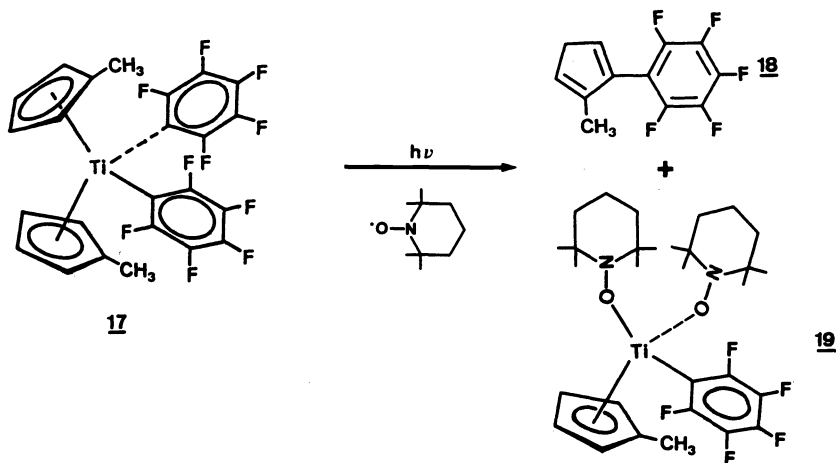Titanocene-bis-aryl compounds have been known for a number of years (ref. 24,25) and their photochemistry has been studied by various groups (ref. 26-29). In fact a number of titanium compounds have been reported to serve as photoinitiators (ref. 30,31). All of the compounds used so far were either oxidatively or thermally unstable or suffered from very poor curing speed. We have found, that when a fluorinated aryl ligand is introduced into the titanocene moiety thermal and oxidative stability is reached and a very efficient curing rate is preserved (ref. 32).

The compounds can easily be prepared according to the procedure given by Stone (ref. 33). The photochemistry of the fluorinated compounds (13), however, is surprisingly different from what is known from the phenyl derivative (14).
From diphenyltitanocene in toluene solution biphenyl and benzene were detected as the major products (ref. 29). In case of the fluorinated compound (17) the photolysis is found to be totally different.
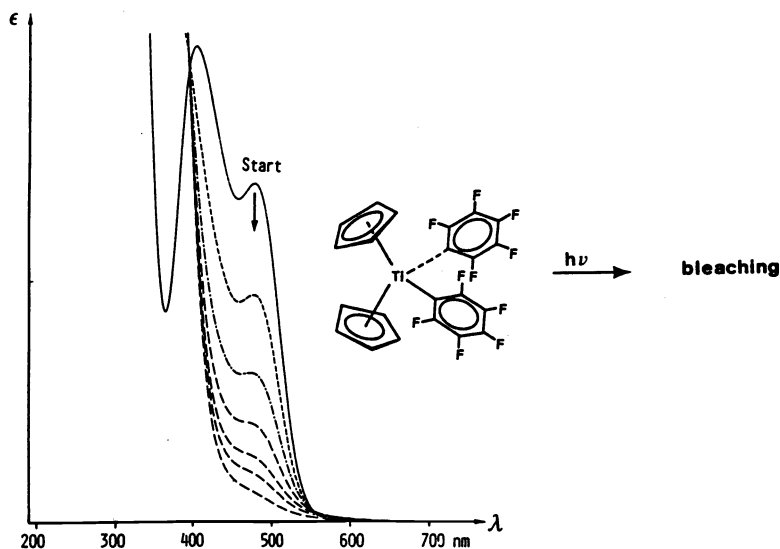The pentafluorophenyl substituted cyclopentadiene (18) is isolated as the main organic product. Furthermore in case of diphenyltitanocene (14) the phenyl radical can be trapped by a radical scavenger and these phenyl radicals are thought to start the polymerisation reaction. In a similar experiment with the fluorinated compound (17) no organic radicals could be trapped.

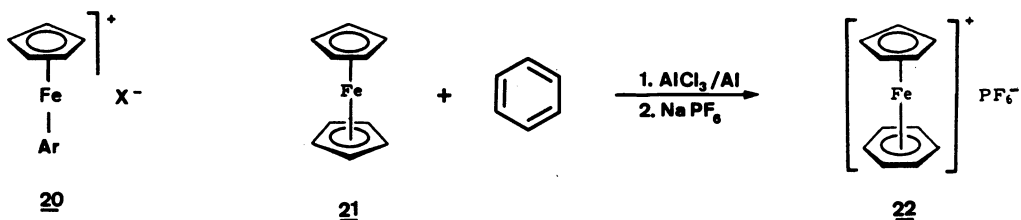From these results it is currently   unclear what in the latter case actually initiates the polymerisation.

Applied as a photoinitiator for vinyl polymerisation our new organometallic radical initiators (13) are among those with the greatest curing speed. A further big advantage of the titanocenes lies in their bleaching.
Their pronounced absorption in the region between 400 and 600 nm gradually decreases with irradiation and there is virtually no absorption in the visible region after the irradiation process is completed. This allows light penetration even into thicker layers and facilitates the curing of polymers of up to 70 μm thickness. It also opens an opportunity to use these photoinitiators in laser-lithography.
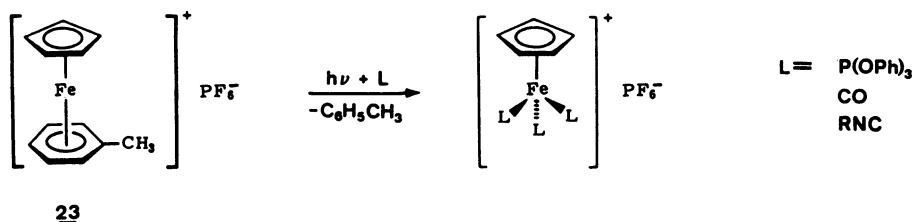

IRON–ARENE PHOTOINITIATORS

In recent years several types of cationic photoinitiators have been described in the literature (ref. 34-36). Crosslinked polyethers with their favourable properties such as thermal stability, mechanical strength and chemical resistance thus became available for coating and imaging applications. A number of organometallic compounds have also been described for this purpose (ref. 37,38). Most of these cationic photoinitiators have certain drawbacks which have so far withheld them from achieving a major break-through. In many cases there is a lack in thermal stability. Our new organometallic iron arene based photoinitiators (20) can overcome most of these shortcomings (ref. 39,40).

In the general formula (20) Ar is an η^6-bound arene ligand and X^- is a non nucleophilic anion. The preparation of these compounds has been described by Nesmeyanov (ref. 41). Gill and Man have subsequently studied ligand exchange reactions replacing the arene ligand by another three suitable ligands (ref. 42-44).

We have found, that photolysis removes the uncharged aromatic ligand and produces a coordinatively unsaturated iron cation. These cationic intermediates are excellent catalysts for the ringopening and polymerisation of epoxide resins. The mechanism for the initiation shown in fig. 1 is therefore assumed.
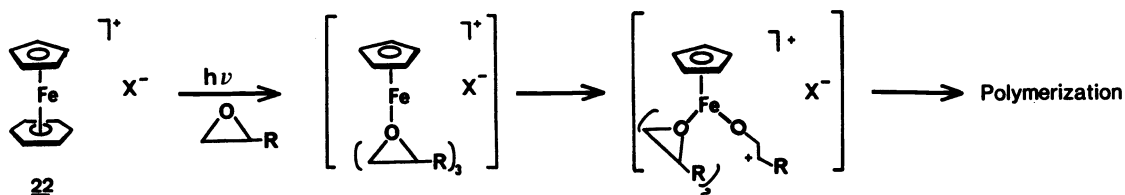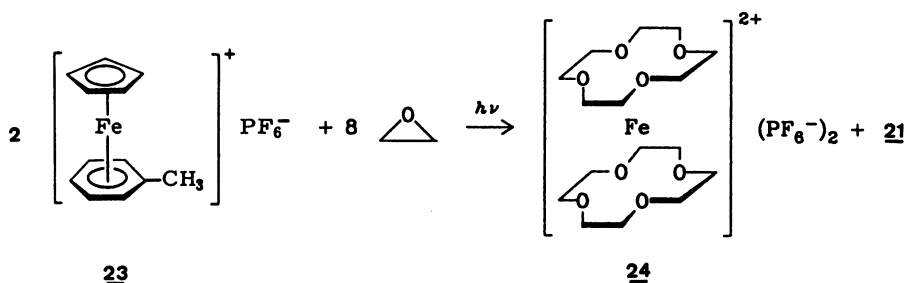

Fig. 1. Postulated mechanism for epoxide polymerisation initiation.

This postulated mechanism was strengthened by a model experiment utilising ethylene oxide as substrate. The photolysis of the toluene complex (23) in presence of ethylene oxide yielded a crystalline paramagnetic solid (24).

An X-ray analysis showed it to be a crown ether complex with an iron central atom (ref. 45), fig. 2.
This led us to believe that after photolytically removing the arene ligand an epoxide can serve as a suitable substitute. Within the coordination sphere of the complex the ringopening will take place and thus the polymerisation is started (see fig. 1).
All of the iron arene photoinitiators have excellent light absorption characteristics in the ultraviolet and the visible region of the spectrum. Their absorption properties can be widely varied by structural changes in the arene ligand, fig. 3.
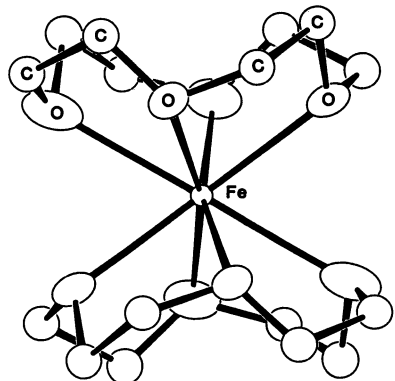

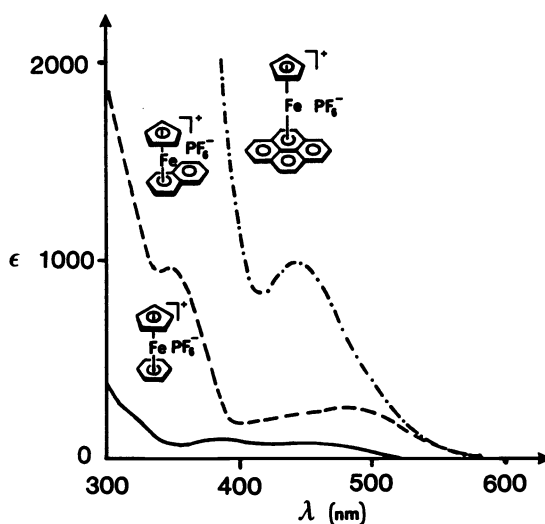Fig. 2. ORTREP-drawing of the structure of the cation of (24).

Fig. 3. Absorption spectra of iron arene complexes in methylenechloride.

CONCLUSION

Photochemistry in industry today is a synthetic tool with great potential. In organic synthesis there are a number of unsolved problems in which a photochemical approach could be the solution. Organometallic photochemistry has practically not been used to solve synthetic problems. The two examples of using organometallic photochemistry for polymerisation initiation seems only the beginning of exploiting a so far unused field.

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