Chapter 1

Introduction

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The olefin metathesis reaction is a powerful method for the construction of new carbon–carbon double bonds. The key component that enables this transformation is a metal alkylidene that mediates both the cleavage of existing carbon–carbon double bonds and their reassembly in new ways (Figure 1.1). In a general scheme, an olefin coordinates to a metal alkylidene complex and undergoes a cycloaddition to give a metallacyclobutane intermediate. This intermediate can then undergo a cycloreversion process in the opposite direction to generate a new olefin and regenerate a metal alkylidene that can react further.[1]

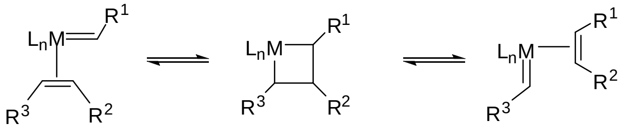


Figure 1.1. General mechanism of olefin metathesis.

Based on the same general mechanism, a number of different metathesis processes can be envisioned (Figure 1.2). Starting from a linear α,ω-diene, ring-closing metathesis (RCM) can form cyclic olefins, or acyclic diene metathesis (ADMET) can form linear polymers. Strained cyclic olefins can participate in ring-opening metathesis polymerization (ROMP) reactions. Alternatively, two different olefins can undergo cross-metathesis (CM) to form a new internal olefin. Examining Figure 1.2 it is easy to see that several processes are interrelated and some driving force is required to push these reversible and thermodynamically controlled reactions to a single product. Typical driving forces include the expulsion of volatile products (e.g., ethylene), the release of ring-strain, or the formation of a more stable olefinic species.

The key to the success of olefin metathesis as a useful methodology was the development of well-defined organometallic catalysts.[2] In the early days of metathesis, the reaction was performed with complex mixtures of transition metal salts, alkylating agents, and supporting media, which combined to form metal alkylidenes.[3] Among the first metal catalysts for olefin metathesis was Tebbe's reagent (**1.1**),[4] which was capable of generating a catalytically

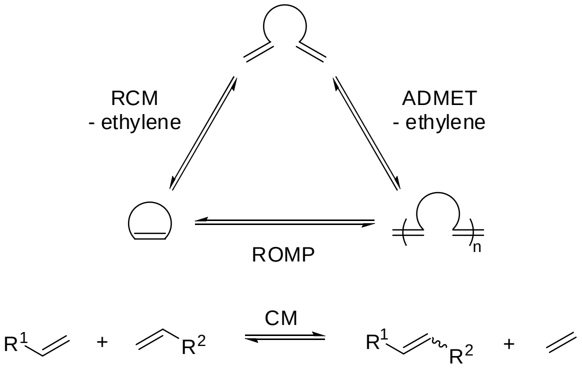
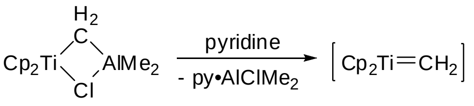
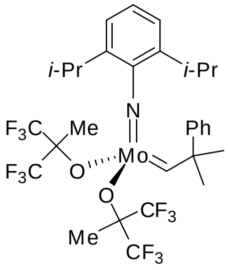


Figure 1.2. Examples of olefin metathesis processes.

active titanium methylidene (**1.2**) (Figure 1.3).[5] Schrock has since developed a family of highly active catalysts based on tungsten and molybdenum that have been widely used.[6] Critical design elements include a bulky alkylidene, and supporting imido and alkoxide ligands. A general problem with early transition metal catalysts is an extreme sensitivity to air and moisture that requires rigorous purification of reagents and extreme care in handling. Polar functionality in substrates can also be problematic with these electrophilic metals.



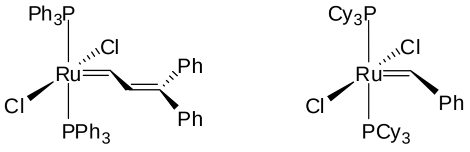
1.1 **1.2**



1.3

Figure 1.3. Early metal catalysts for olefin metathesis.

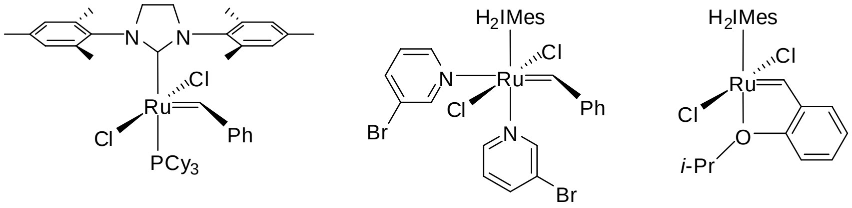
Before the 1990s, practically all olefin metathesis catalysts were based on early transition metals; however, the observation that ruthenium salts, such as $[Ru(H_2O)_6](OTs)_2$, were active ROMP catalysts led to the exploration of late metal systems for olefin metathesis.[7] The first example of a well-defined ruthenium catalyst (**1.4** in Chart 1.1) was limited in scope to reaction with highly strained systems like norbornenes.[8] Nevertheless this catalyst has the same general framework as today's commonly used catalysts: a ruthenium alkylidene, two halide ligands, and two neutral ligands.[9] When the PPh_3 ligands were exchanged for the more electron-donating PCy_3 ligands and the vinyl carbene was replaced with a benzylidene, the substrate scope was greatly increased.[10] Catalyst **1.5** was much more active than **1.4**, reacting with unstrained olefins and carrying out a wide range of organic transformations.[11] Most importantly, ruthenium-based systems were significantly more tolerant of oxygen and moisture than the early metal systems. This robust character allowed for easier handling and enabled the synthetic chemist to begin to exploit the potential of olefin metathesis.



1.4 **1.5**

Chart 1.1. Early Ruthenium-Based Metathesis Catalysts

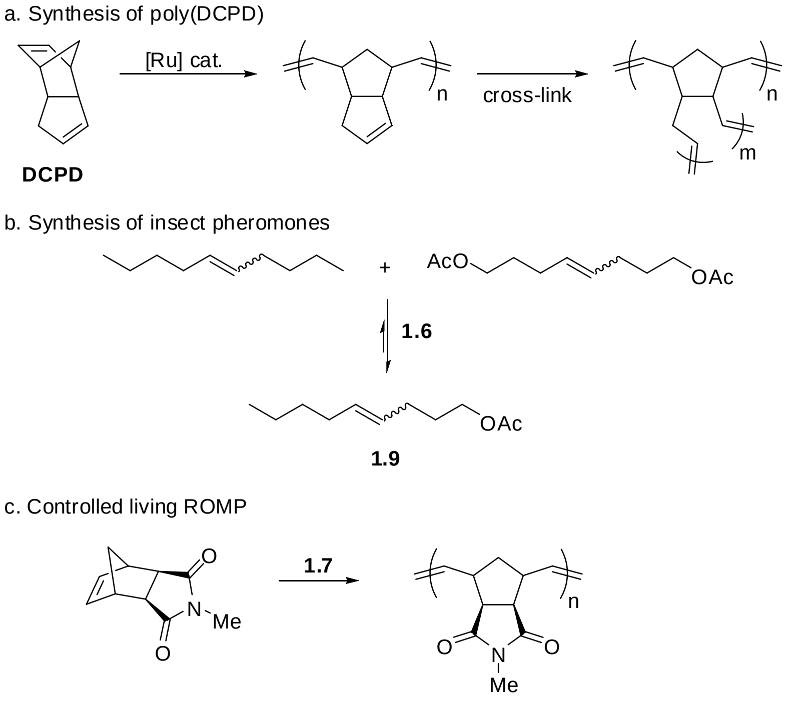
The next major step forward was the replacement of one phosphine with a strongly electron-donating *N*-heterocyclic carbene (NHC) ligand to provide catalyst **1.6** (Chart 1.2).[12] This change increased the overall activity, rivaling molybdenum systems for the first time. The higher activity also expanded the substrate scope to include olefins that were previously unreactive, particularly bulky, or electron-deficient olefins. Further modifications to the catalyst framework, such as the incorporation of pyridine ligands, provided fast-initiating catalysts.[13] The development of phosphine-free systems (e.g. **1.8**) has resulted in catalysts with higher stability.[14] Further efforts have produced catalysts well-suited for a diverse range of applications including: asymmetric catalysis,[15] aqueous olefin metathesis,[16] and the formation of sterically hindered olefins.[17]



1.6 **1.7** **1.8**

Chart 1.2. NHC-Based Olefin Metathesis Catalysts

With the advent of this class of environmentally tolerant Ru metathesis catalysts many potential applications have emerged (Figure 1.4). The ROMP of dicyclopentadiene (DCPD) is a commercially important process that transforms an inexpensive monomer into a polymer that is extremely hard and chemically inert. Products ranging from truck parts to baseball bats have been manufactured from this tough material.[18] In the field of agrochemicals, cross metathesis has been used to synthesize insect pheromones that contain carbon–carbon double bonds.[19] A component of the peach twig borer pheromone, 5-decenyl acetate (**1.9**), can be obtained in high yield from CM of simple starting materials. The living polymerization of norbornenes catalyzed by **1.7** has enabled the synthesis of functionalized polymers tailored with extremely accurate control over molecular weight distribution.[20]


a. Synthesis of poly(DCPD)

b. Synthesis of insect pheromones

c. Controlled living ROMP

Figure 1.4. Selected applications of olefin metathesis.

This thesis focuses on three areas necessary for the further development of olefin metathesis. Chapter 2 describes the synthesis of new latent olefin metathesis catalysts for high temperature applications. The use of donor ligands chelated through the ruthenium alkylidene allows for initiation rates to be reduced. A study of the mechanism of initiation of catalysts with chelating ligands is the focus of Chapter 3. Several important mechanistic distinctions are observed between these systems and phosphine-containing catalysts, such as **1.5** and **1.6**. The differences in initiation mechanism have implications for future catalyst development. Chapter 4 explores the extension of ROMP to include polymerization of low-strain olefins with medium-sized (5-, 6-, and 7-membered) rings. The effect of ring substitution on strain energy was studied, and symmetrically substituted cyclic olefins were polymerized to give regioregular materials. Appendix 1 describes a standard system of characterization for olefin metathesis catalysts that can be used as a tool for the evaluation of modifications to catalyst structure.

References and Notes

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