

文章编号: 1001-3555(2012)03-0284-08

五羰基铁催化羰化反应的研究进展

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关键词: 五羰基铁; 催化; 羰基化;

中图分类号: O643.3 文献标识码: A

1827年, 丹麦药剂师 Zeise 在加热 PtCl_2/KCl 的乙醇溶液时得到了世界上第一个金属有机化合物, 即后来人们命名的 Zeise 盐^[1]. 1890年, Mond^[1]等在研究一氧化碳(CO)对不锈钢阀门的腐蚀原因时发现: CO与镍粉反应生成的四羰基镍($\text{Ni}(\text{CO})_4$)对阀门具有腐蚀作用. 1891年, 他们又发现并合成了五羰基铁($\text{Fe}(\text{CO})_5$), 从而解释了长期装CO的钢瓶会发生爆炸的原因. 从 $\text{Fe}(\text{CO})_5$ 的发现到其工业化生产已经历多年, 但直到 $\text{Fe}(\text{CO})_5$ 被人们发现可作为内燃机燃油的抗爆剂这一重要应用时, $\text{Fe}(\text{CO})_5$ 的制备及其实际功效才开始日益被重视^[2]. $\text{Fe}(\text{CO})_5$ 相对于其它羰基金属因其简单易得、成本低廉等诸多优点而引起人们对 $\text{Fe}(\text{CO})_5$ 在催化领域方面研究的关注和兴趣. 关于 $\text{Fe}(\text{CO})_5$ 在羰化反应中的催化作用, 人们做了大量卓有成效的工作. 我们将从以下几个部分对 $\text{Fe}(\text{CO})_5$ 催化羰化反应进行详细的概述和总结.

羰基化反应是在催化剂的作用之下, CO与不饱和烃、含活泼C-Y键($Y = \text{OH}, \text{OR}, \text{X}$ 等)的化合物生成羰基化合物的反应, 生成的产物因具有重要的应用价值而备受产业界和学术界的重视^[1]. 它分为两类, 第一类是在含活泼氢化合物如水、醇、氨存在下, CO与不饱和烃反应, 生成酸、酯、酰胺(图1).

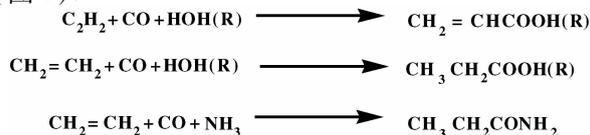


图1 乙烯的羰基化反应

Fig. 1 Carbonylation reaction of ethylene

第二类, 是CO插入到醇、醚、环氧化合物、酯、酐、卤代烃等化合物中生成羧酸、酯、酐(图2)等的反应.

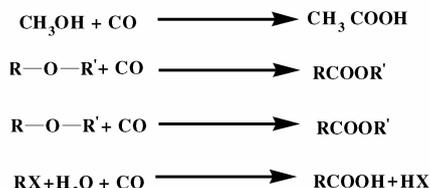


图2 醇、醚、卤代烃的羰基化反应

Fig. 2 Carbonylation reaction of alcohol, ether and halogenated hydrocarbons

1 烯烃的羰基化反应

1938年, 德国科学家 Otto Rölen 在150℃、10 MPa的条件下将乙烯与合成气通过钴催化剂合成了丙醛^[3], 继而引发了乙烯羰基化的研究热潮.

1977年, Gian^[4]等采用五羰基铁等催化剂详细开展了乙烯的羰基化反应, 并对比分析了如下两个不同的合成步骤及其所采用的催化剂(图3), 文章中还特别指出: 碱性环境下的五羰基铁的催化活性相比于单纯的合成气环境有较大提高且实验条件温和可控.

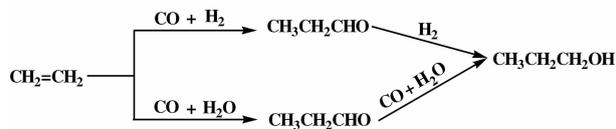


图3 乙烯羰基化反应合成1-丙醇

Fig. 3 Synthesis of 1-propanol by ethylene carbonylation reaction

收稿日期: 2012-04-02; 修回日期: 2012-04-26.

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1982年, Barborak^[5]等进一步探讨了乙烯的羰基化反应并给出了可能的反应路线(图4).

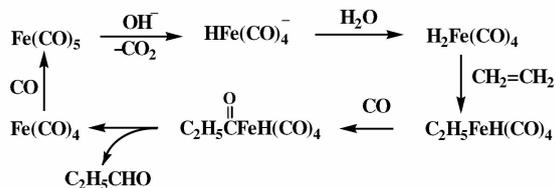


图4 乙烯的羰基化反应过程

Fig. 4 The reaction process of ethylene carbonylation

1985年, Halpern^[6]等研究探讨了五羰基铁催化一般烯烃的反应, 其一般通式如图5.

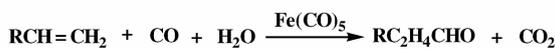


图5 烯烃的羰基化反应

Fig. 5 Carbonylation reaction of olefin

1994年, 徐世书^[7]报道称乙烯基环丙烷经五羰基铁羰基化可制得高产率的环己烯酮(图6).

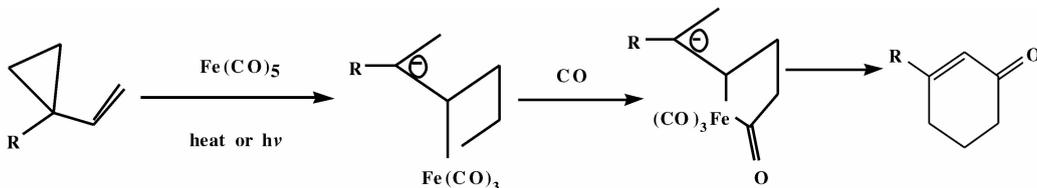


图6 乙烯基环丙烷的羰基化反应

Fig. 6 Carbonylation reaction of the vinyl cyclopropane

自从20世纪50年代二茂铁^[8]发现以来, 环戊二烯基金属有机化合物成为研究最多的一类金属有机化合物. 二聚环戊二烯与五羰基铁可发生如下反

应, 得到顺式、反式桥连体以及非桥连异构体的混合物^[9,10](图7).

20世纪80年代初茂金属催化剂的发现, 使桥

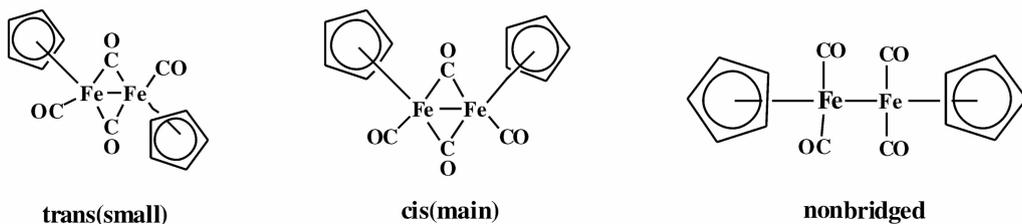
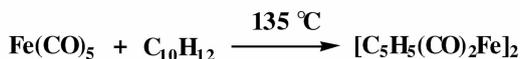


图7 环戊二烯二聚体与五羰基铁的反应

Fig. 7 The reaction of dicyclopentadiene with pentacarbonyl iron

连二环戊二烯基金属有机化合物的研究更加深入和广泛^[11, 12]. 相对于简单环戊二烯和单桥连二环戊二烯而言, 双桥连二环戊二烯由于其比较僵硬的特殊结构, 引起了人们的广泛兴趣. 特别是近年来, 由于这类配体的合成方法日趋完善, 促进了各种双桥连二环戊二烯基金属有机化合物的合成、结构及应用研究, 并发现这类金属有机化合物在结构和催化等方面都表现出一些特殊的性质. 对于桥连二环戊二烯基双核金属有机化合物, 由于桥原子的引入, 使两个茂环相互影响、相互制约, 同时两个金属原子也被束缚在一起, 从而导致桥连双茂金属有

机化学具有丰富多彩的内容并且展现出广泛的应用前景, 如五羰基铁与二聚环戊二烯反应生成的 $[\text{C}_5\text{H}_5(\text{CO})_2\text{Fe}]_2$ ^[11]可催化烯烃的羰基化反应(图8).

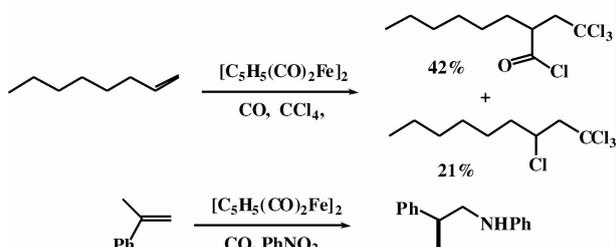


图8 五羰基铁衍生物的羰基化反应

Fig. 8 Carbonylation reaction of pentacarbonyl iron derivatives

此外,五羰基铁还可与较复杂的炔烃发生羰基化反应^[13-20].

2 炔烃的羰基化反应

炔烃在五羰基铁的催化作用下发生羰基化反应生成不饱和的羧酸及其衍生物,结果见表1.

2008年,Periasamy^[21-23]等直接利用五羰基铁与炔烃羰基化反应制得环丁烯二酮,其具体合成反

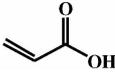
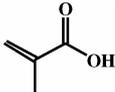
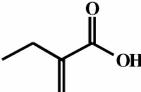
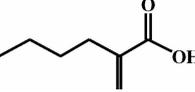
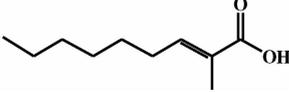
应见图9.

文章中以不同的炔烃底物合成了一系列环丁烯酮的同系物并探索了其反应过程,该方法所需的原料氢氧化钠(NaH)和 $\text{Fe}(\text{CO})_5$ 价格便宜、简单易得,为环丁烯酮及其衍生物的发展、研究开拓了更广阔的空间.

2008年,Mathur^[24,25]等利用五羰基铁与烯炔炔反应制得苯醌衍生物(图10).

表1 炔烃的羰基化反应结果^[1]

Table 1 Results of carbonylation reactions of alkynes

Entry	Substrate	Product	Yield(%)
1			95
2			50
3			45
4			35
5			32

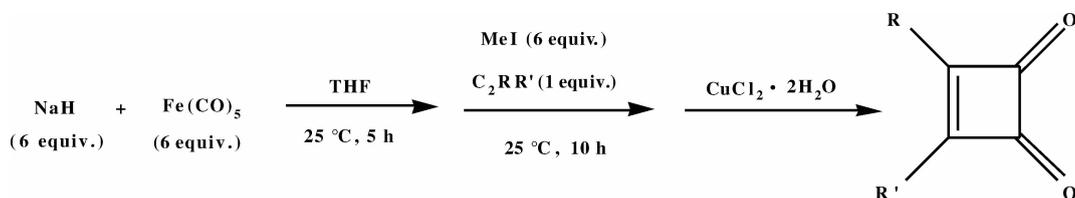


图9 五羰基铁、NaH与炔烃制备环丁烯二酮

Fig.9 Preparation of ring-butene-dione with pentacarbonyl iron, NaH and alkynes

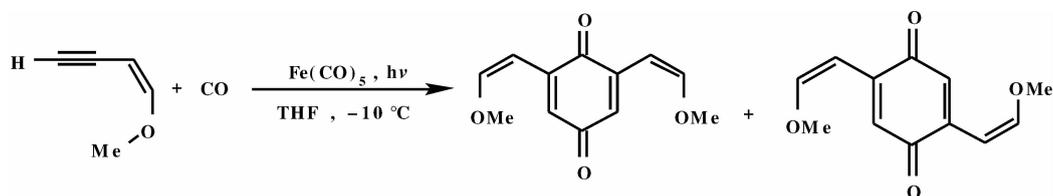


图10 五羰基铁催化制备苯醌

Fig.10 Preparation of benzoquinone with catalysis of pentacarbonyl iron

2009年, Driller^[26]等以反应的经济性和环境友好性等因素为出发点, 以五羰基铁为催化剂开展其羰基化反应, 一步反应制得一系列收率和选择性都很好的内酰胺(图11)。

2009年, Mathur^[27]等利用五羰基铁的配位整合和羰基化的双重作用成功合成了如下化合物(1-7)(图12, 13)。

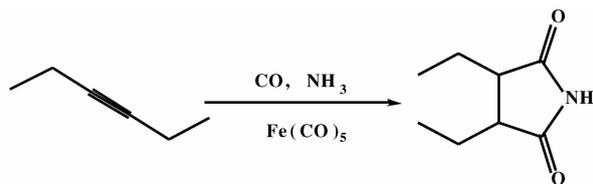


图11 五羰基铁催化制备内酰胺

Fig. 11 Preparation of lactam with catalysis of pentacarbonyl iron

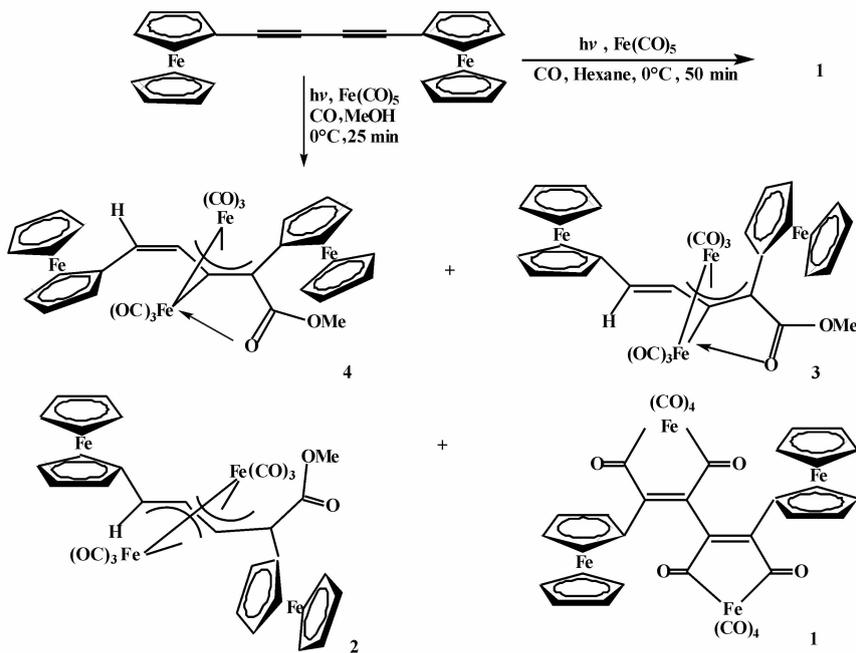


图12 1,4-二茂铁-1,3-丁二炔与 Fe(CO)₅和CO在MeOH中的光催化反应

Fig. 12 Photoreactions of 1,4-diferrocenyl-1,3-butadiyne with Fe(CO)₅ and CO in MeOH

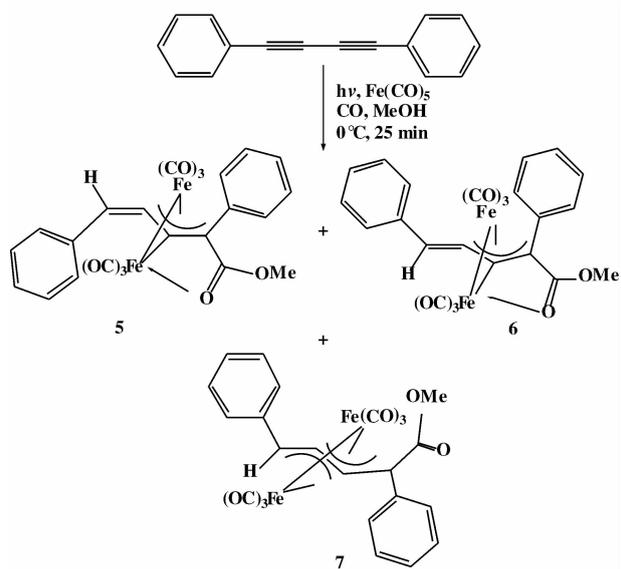


图13 1,4-二苯基-1,3-丁二炔与 Fe(CO)₅和CO在MeOH中的光催化反应

Fig. 13 Photoreactions of 1,4-diphenyl-1,3-butadiyne with Fe(CO)₅ and CO in MeOH

2010年, Mathur^[28]等以五羰基铁为催化剂、温和的温度和压力条件下, 一锅法合成了高收率的 α,β -乙烯酯和烷氧基取代的 γ -内酯(图14)。

2011年, Beesu^[29]等在叔丁醇钾(*t*-BuOK)的碱性环境下, 分别以五羰基铁和九羰基二铁的催化羰基化反应合成制备了环丁烯二酮(图15), 结果表明: 反应条件相似的情况下, 五羰基铁催化羰基化的产物的收率和选择性都高于九羰基二铁. 该实验的反应条件较之于前人的更温和, 选择性更好, 具体反应见下图15。

3 卤代烃的羰基化反应

五羰基铁催化羰基化卤代烃得到酰卤. 水存在下得到羧酸, 醇存在下得到酯, 胺存在下得到酰胺, 通常用NaOH、RONa、R₃N中和反应生成的HX, 其反应通式^[1]见图16。

无水条件下, 五羰基铁催化羰基化醚得到酯, 继续反应得到酸酐^[1](图17)。

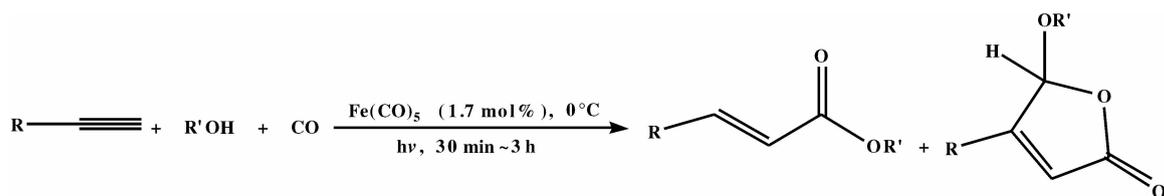
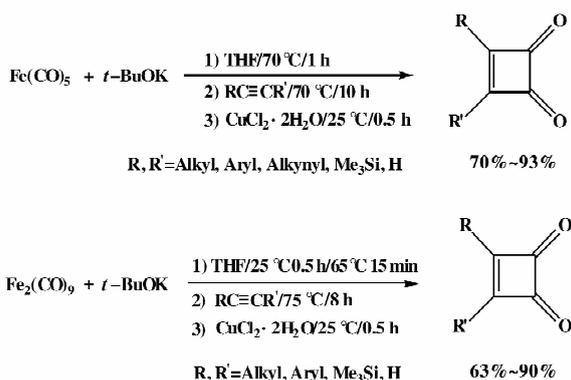
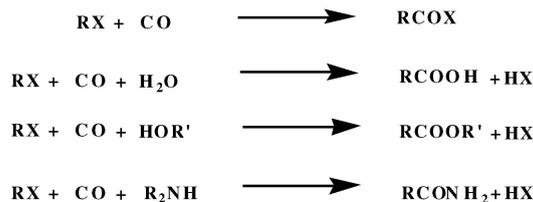
图 14 五羰基铁催化制备 α, β -乙烯酯和 γ -内酯Fig. 14 Formation of α, β -vinylester and γ -lactones with catalysis of pentacarbonyl iron图 15 $\text{Fe}(\text{CO})_5$ ($\text{Fe}_2(\text{CO})_9$) 在 $t\text{-BuOK}$ 中
与炔烃制备环丁烯二酮Fig. 15 Preparation of ring-butene-dione with $\text{Fe}(\text{CO})_5$
($\text{Fe}_2(\text{CO})_9$) and alkynes in $t\text{-BuOK}$ 

图 16 卤代烃的羰基化反应

Fig. 16 Carbonylation reaction of halogenated hydrocarbons

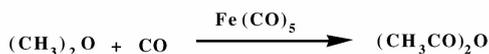


图 17 五羰基铁催化醚制备酸酐

Fig. 17 Preparation of anhydride with catalysis of
pentacarbonyl iron of ether

催化卤代烃来合成醛^[30-33]、羧酸及其衍生物^[34-42]是羰基化反应的又一个重要应用, Collman^[43,44]等详细研究了五羰基铁与卤代烃的羰基化反应,并给出了如下反应过程(图 18)。

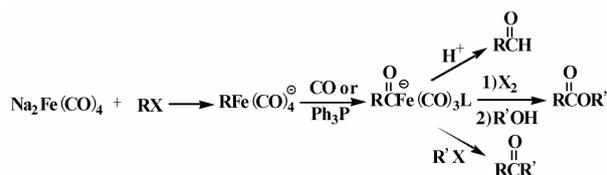


图 18 卤代烃羰基化反应过程

Fig. 18 The reaction process of carbonylation of halogenated
hydrocarbons

在三苯基磷的存在下,四氢呋喃(THF)溶剂中, $\text{Na}_2[\text{Fe}(\text{CO})_4]$ (由 $\text{Fe}(\text{CO})_5$ 和 NaOH 反应制得)和多种卤代烃反应,可得到产率较高的醛酮、羧酸^[45](图 19, 20)。

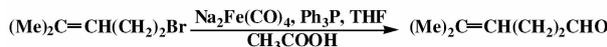


图 19 羰基铁催化溴代烃制备醛

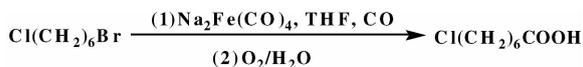
Fig. 19 Preparation of aldehyde with carbonyl iron catalyzing
bromo hydrocarbon

图 20 羰基铁催化卤代烃制备羧酸

Fig. 20 Preparation of carboxylic acid with carbonyl iron
catalyzing halogenated hydrocarbons

推测其反应机理:四羰基合铁化钠先与卤代烃反应生成铁配合物,接着一个羰基由铁上转移插入到铁与烷基之间形成一个酰基化的铁,再与醋酸的质子反应,生成酰基铁的氢化物,再还原消除可得到醛,具体见下图 21。

1984 年, Tustin^[46]等以碱性环境中的 $\text{Fe}(\text{CO})_5$ 与 CO 、羟基试剂反应制备了羧酸衍生物,具体见图 22。

该反应条件温和, Tustin 等又以溴化苄为反应底物得到了高产率的芳醛酯(图 23)。

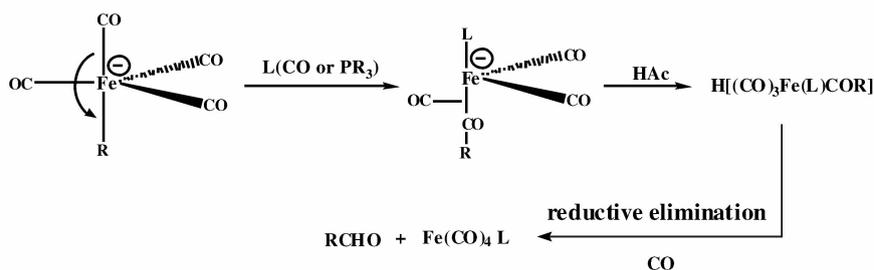
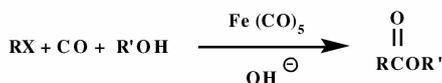
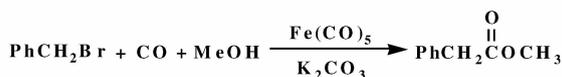


图 21 羰基铁催化卤代烃的反应机理

Fig. 21 Reaction mechanism of with carbonyl iron catalyzing halogenated hydrocarbons

图 22 $\text{Fe}(\text{CO})_5$ 催化卤代烃合成酯Fig. 22 Synthesis of ester with $\text{Fe}(\text{CO})_5$ catalyzing halogenated hydrocarbons图 23 $\text{Fe}(\text{CO})_5$ 催化溴化苄合成酯Fig. 23 Synthesis of ester with $\text{Fe}(\text{CO})_5$ catalyzing benzyl bromide

他们还考察了 K_2CO_3 、 Na_2CO_3 、 Li_2CO_3 、 KOH 、 NaOH 、 NaOCH_3 等多种碱的影响, 实验结果表明: K_2CO_3 环境中, 五羰基铁催化羰化卤代烃的产物的产率最高, 选择性最好。

1989 年, Hashiba^[47] 等改用电化学方法利用五羰基铁催化羰化反应合成酯, 相对于传统化学方法其产率提高了 30% 多, 同时该电化学方法还有效避免了诸如传统方法中底物的热不稳定性等缺点, 因此其反应底物的选择更灵活、高效。

2001 年, Dolhem^[48] 等同样采用电化学方法合成制备了高产率的不对称酮, 该反应操作简单、实验条件温和。

4 结论与展望

在羰基化反应的研究方面, 人们往往极大地关注催化剂的高效选择性与其可重复利用性, 而反应过程的可操作性、经济实用性、环境友好性等因素也不容忽视。五羰基铁在羰基金属中因其简单易得、成本低廉等诸多优点, 使得五羰基铁在催化领域方面的研究具有巨大的发展潜力。相信未来五羰基铁的应用研究价值会陆续为人们所知。

参考文献:

- [1] a. He Ren (何仁), Tao Xiao-chun (陶晓春), Zhang Zhao-guo (张兆国). *Metal Organic Chemistry (金属有机化学)* [M]. *East China University of Science and Technology Press* (华东理工大学出版社), 2007. **20**: 219 - 224

b. Liu Jian-ming(刘建明), Wang Jing-fang(王京芳), Yue Yuan-yuan(岳园园), *et al.* $\text{Pd}_2(\text{dba})_3/\text{Et}_3\text{N}$: An Efficient catalyst system of carbonylative sonogashira coupling reaction for synthesis of α , β -alkynyl ketones[J]. *J. Mol. Catal. (China)* (分子催化), 2011, **25**(1): 17 - 23

c. Zhao Mei-ting(赵美廷), Zhou Jian-wei(周剑伟), Li Zhen(李臻), *et al.* Polyoxo metalates based supported inoic ziquid catalytis for alcohol oxidasion with hydrogen penoxiele [J]. *J. Mol. Catal. (China)* (分子催化), 2011, **25**(2): 97 - 104
- [2] Zheng C B, Sturgeon R E, Brophy C S, *et al.* High-yield UV-photochemical vapor generation of iron for sample introduction with inductively coupled plasma optical emission spectrometry [J]. *Anal. Chem.*, 2010, **82**(7): 2 996 - 3 001
- [3] Rölen O. Synthesis of propionaldehyde with ethylene and CO/H_2 . DE [P]. 849 548, 1938
- [4] Gian H F, Tong S L. Determination of traces of arsenic in water by arsine generation and radiometric analysis [J]. *Anal. Chim. Acta.*, 1977, **89**(1): 151 - 156
- [5] Barborak J C, Cann K. An alternate binuclear mechanism for aldehyde formation in the reppe-modified hydroformylation reaction [J]. *Organometallics*, 1982, **1**(12): 1 726 - 1 728
- [6] Halpern J. Oxidation of organometallic compounds [J]. *Angew. Chem. Int. Edit.*, 1985, **24**(4): 274 - 282
- [7] Xu Shi-xu (徐世书). Research on carbonyl compounds of pent coordinated iron (铁五配位羰基化合物的研究)

- [J]. *Journal of Qiongzhou University* (琼州大学学报), 1994, **39**(1): 189 - 192
- [8] Kealy T J, Pauson P L. A new type of organo-iron compound [J]. *Nature*, 1951, **168**(4285): 1 039 - 1 040
- [9] Manning A R. Structure of bis-pi-cyclopentadienyldi-Iron tetracarbonyl in solution [J]. *J. Chem. Soc. A.*, 1968, 1 319 - 1 324
- [10] Bryan R F, Greene P T. Metal-metal bonding in Co-ordination complexes. 9. crystal structure of trans-di-mu-carbonyl-dicarbonyldi-pi-cyclopentadienyldi-iron (Fe-Fe), a redetermination [J]. *J. Chem. Soc. A.*, 1970, 3 064 - 3 081
- [11] Mohring P C, Coville N J. Homogeneous group-4 metallocene ziegler-natta catalysts the influence of cyclopentadienyl-ring substituents [J]. *J. Organomet. Chem.*, 1994, **479**: 1 - 29
- [12] Brintzinger H H, Fischer D, Mulhaupt R, *et al.* Stereospecific olefin polymerization with chiral metallocene catalysts [J]. *Angew. Chem. Int. Edit.*, 1995, **34**(11): 1 143 - 1 170
- [13] Eaton B E, Rollman B, Kaduk J A. The 1st catalytic iron-mediated [4 + 1] cyclopentenone assembly-stereoselective synthesis of 2, 5-dialkylidenecyclo-3-pentenones [J]. *J. Am. Chem. Soc.*, 1992, **114**(15): 6 245 - 6 246
- [14] Sigman M S, Eaton B E. Catalytic iron-mediated [4 + 1] cycloaddition of diallenes with carbon monoxide [J]. *J. Am. Chem. Soc.*, 1996, **118**(47): 11 783 - 11 788
- [15] Sigman M S, Kerr C E, Eaton B E. Catalytic iron-mediated carbon-oxygen and carbon-carbon bond formation in [4 + 1] assembly of alkylidenebutenolides [J]. *J. Am. Chem. Soc.*, 1993, **115**(16): 7 545 - 7 546
- [16] Sigman M S, Eaton B E, Heise J D, *et al.* Low-temperature study of the iron-mediated [4 + 1] cyclization of allenyl ketones with carbon monoxide [J]. *Organometallics*, 1996, **15**(12): 2 829 - 2 832
- [17] Sigman M S, Eaton B E. The first iron-mediated catalytic carbon-nitrogen bond formation-[4 + 1] cycloaddition of allenyl imines and carbon-monoxide [J]. *J. Org. Chem.*, 1994, **59**(24): 7 488 - 7 491
- [18] Taber D F, Kanai K, Jiang Q, *et al.* Enantiomerically pure cyclohexenones by Fe-mediated carbonylation of alkenyl cyclopropanes [J]. *J. Am. Chem. Soc.*, 2000, **122**(28): 6 807 - 6 808
- [19] Stockis A, Weissberger E. Metal assisted ring expansions-stereospecific expansion of pinene induced by Fe(CO)₅ [J]. *J. Am. Chem. Soc.*, 1975, **97**(15): 4 288 - 4 292
- [20] Wenz M, Grossbach D, Beitzel M, *et al.* An approach towards enantiomerically pure taxoidic A, B-ring fragments [J]. *Synthesis-Stuttgart*, 1999, 607 - 614
- [21] Periasamy M, Beesu M, Raj D S. A simple and convenient method for the synthesis of cyclobutenediones from alkynes using new Fe(CO)₅/NaH/MeI reagent system [J]. *J. Organomet. Chem.*, 2008, **693**(17): 2 843 - 2 846
- [22] Periasamy M, Mukkanti A, Raj D S. Novel synthesis of acyloxyferrole complexes from alkynes and their conversion to cyclobutenediones [J]. *Organometallics*, 2004, **23**(3): 619 - 621
- [23] Pearson J, Cooke J, Takats J, *et al.* Alkyne ligand enhancement of the substitution lability of mononuclear osmium, ruthenium, and iron carbonyls [J]. *J. Am. Chem. Soc.*, 1998, **120**(7): 1 434 - 1 440
- [24] Mathur P, Avasare V D, Mobin S M. Iron pentacarbonyl assisted photochemical route to 2,5 and 2,6-divinyl-substituted 1,4-benzoquinones from 1-ene-3-yne [J]. *Tetrahedron*, 2008, **64**(37): 8 943 - 8 946
- [25] Mathur P, Singh A K, Singh V K, *et al.* Coupling reactions of ferrocenylacetylene with mononuclear metal carbonyls Fe(CO)₅ and M(CO)₆ (M = Mo, W): synthesis and characterization of [Fe(CO)₂]{eta(5)-2,5-Fc(2)C(5)H(2)CO}C(Fc)=CH], [Fe(CO)₂]{eta(2):eta(2)-2,5-Fc(2)C(4)H(2)Fe(CO)₃}-mu-CO], [Fe(CO)₃]{eta(2):eta(2)-2,5-Fc(2)C(4)H(2)CO}], 1, 2, 4-triferrocenylbenzene, 2,5-diferrocenylthiophene, and 2,5-diferrocenylselenophene [J]. *Organometallics*, 2005, **24**(20): 4 793 - 4 798
- [26] Driller K M, Klein H, Jackstell R, *et al.* Iron-catalyzed carbonylation: selective and efficient synthesis of succinimides [J]. *Angew. Chem. Int. Edit.*, 2009, **48**(33): 6 041 - 6 044
- [27] Mathur P, Avasare V D, Mobin S M. Iron pentacarbonyl promoted addition of CO and MeOH to 1,4-disubstituted-1,3-butadiyne and formation of vinylallyl and butatriene ligand systems [J]. *J. Clust. Sci.*, 2009, **20**(2): 399 - 415
- [28] Mathur P, Joshi R K, Jha B, *et al.* Towards the catalytic formation of alpha, beta-vinylesters and alkoxy substituted gamma-lactones [J]. *J. Organomet. Chem.*, 2010, **695**(24): 2 687 - 2 694
- [29] Beesu M, Periasamy M. Reactive iron carbonyl reagents via reaction of metal alkoxides with Fe(CO)₅ or Fe

- (2)(CO)(9): synthesis of cyclobutenediones via double carbonylation of alkynes [J]. *J. Org. Chem.*, 2011, **76**(2): 543–549
- [30] Ryu I, Kusano K, Ogawa A, *et al.* Free-radical carbonylation-efficient trapping of carbon-monoxide by carbon radicals [J]. *J. Am. Chem. Soc.*, 1990, **112**(3): 1 295–1 297
- [31] Ryu I, Hasegawa M, Kurihara A, *et al.* Free-radical carbonylation by tmss mediated process [J]. *Synlett*, 1993, 143–145
- [32] Gupta V, Kahne D. Direct introduction of Ch₂oh by intermolecular trapping of Co [J]. *Tetrahedron Lett.*, 1993, **34**(4): 591–594
- [33] Tsunoi S, Ryu I, Fukushima H, *et al.* Free-radical carbonylation using a Zn(Cu) induced reduction system [J]. *Synlett*, 1995, 1 249–1 260
- [34] Yoshisat E, Tsutsumi S. Reactions of benzyl halides with nickel carbonyl in various media [J]. *J. Org. Chem.*, 1968, **33**(2): 869–870
- [35] Baker R. Pi-allylmetal derivatives in organic synthesis [J]. *Chem. Rev.*, 1973, **73**(5): 487–530
- [36] Alper H, Hashem K, Heveling J. Selective phase-transfer and palladium(O)-catalyzed carbonylation, carbalkoxylation, and reduction reactions [J]. *Organometallics*, 1982, **1**(6): 775–778
- [37] Mizushima E, Hayashi T, Tanaka M. Palladium-catalysed carbonylation of aryl halides in ionic liquid media; high catalyst stability and significant rate-enhancement in alkoxycarbonylation [J]. *Green. Chem.*, 2001, **3**(2): 76–79
- [38] Mizushima E, Hayashi T, Tanaka M. Environmentally benign carbonylation reaction; palladium catalyzed hydroxycarbonylation of aryl halides and benzyl chloride derivatives in Ionic liquid media [J]. *Top. Catal.*, 2004, **29**: 163–166
- [39] Nagahara K, Ryu I, Komatsu M, *et al.* Radical carboxylation: ester synthesis from alkyl iodides, carbon monoxide, and alcohols under irradiation conditions [J]. *J. Am. Chem. Soc.*, 1997, **119**(23): 5 465–5 466
- [40] Ryu I, Nagahara K, Kambe N, *et al.* Metal catalyst-free by design. the synthesis of amides from alkyl iodides, carbon monoxide and amines by a hybrid radical/ionic reaction [J]. *Chem. Commun.*, 1998, 1 953–1 954
- [41] Trzeciak A M, Wojtkow W, Ciunik Z, *et al.* Low-pressure carbonylation of benzyl bromide with palladium complexes modified with PNS (PNS = Ph₂PCH₂CH₂C(O)NHC(CH₃)₂CH₂SO₃Li) or P(OPh)₃. structural identification of palladium-catalyst intermediate [J]. *Catal. Lett.*, 2001, **77**(4): 245–249
- [42] Ryang M, Yoshida K, Yokoo H, *et al.* Reaction of carbon monoxide with organometallic compounds. X. reaction of carbon monoxide with phenyl derivatives of transition metals [J]. *B. Chem. Soc. Jpn.*, 1965, **38**(4): 636–639
- [43] Collman J P, Finke R G, Cawse J N, *et al.* Oxidative-addition reactions of Na₂Fe(CO)₄ supernucleophile [J]. *J. Am. Chem. Soc.*, 1977, **99**(8): 2 515–2 526
- [44] Collman J P, Finke R G, Cawse J N, *et al.* Lewis acid-catalyzed [RFe(CO)₄]-alkyl migration reactions-mechanistic investigation [J]. *J. Am. Chem. Soc.*, 1978, **100**(15): 4 766–4 772
- [45] Song Yin-zhu (宋银柱), *et al.*(译). Coordination Chemistry (配位化学) [M]. *Peking University Press* (北大出版社), 1982. 247
- [46] Tustin G C, Hembre R T. Catalytic uses of Fe(CO)₅-formation of carboxylic-acid derivatives [J]. *J. Org. Chem.*, 1984, **49**(10): 1 761–1 764
- [47] Hashiba S, Fuchigami T, Nonaka T. Electroorganic synthesis using organometals. 1. cathodic ester formation from alcohols and alkyl-halides in the presence of catalytic amounts of iron(0) pentacarbonyl at atmospheric-pressure of carbon-monoxide [J]. *J. Org. Chem.*, 1989, **54**(10): 2 475–2 476
- [48] Dolhem E, Barhdadi R, Folest J C, *et al.* Nickel catalysed electrosynthesis of ketones from organic halides and iron pentacarbonyl. Part 2: unsymmetrical ketones [J]. *Tetrahedron*, 2001, **57**(3): 525–529