Catalysis Letters Vol. 102, Nos. 3–4, August 2005 (© 2005)
DOI: 10.1007/s10562-005-5854-6

The Hydroamination of methyl acrylates with amines over zeolites

Jana Horniakova[a], Kenichi Komura[a], Hisashi Osaki[a], Yoshihiro Kubota[a,b], and Yoshihiro Sugi[a,*]

[a]*Department of Materials Science and Technology, Faculty of Engineering, Gifu University, Gifu, 501-1193 Japan*
[b]*Department of Materials Science and Engineering, Graduate School of Engineering, Yokohama National University, Yokohama 240-8501 Japan*

Received 16 December 2004; accepted 29 March 2005

H-form zeolites, H-FAU and H-BEA have been studied as heterogeneous catalysts for the hydroamination. They catalyzed the reaction of methyl acrylate with aniline to give *N*-[2-(methoxycarbonyl)ethyl]aniline (**1**) as a main product. H-BEA and H-FAU zeolites efficiently catalyzed the hydroamination to afford *anti*-Markovnikov adduct as a main product. The conversion of aniline around 55–85% was achieved within 18 h over H-BEA and H-FAU zeolites with SiO_2/Al_2O_3 molar ratio of 25–30; however, the formation of *N,N*-bis[2-(methoxycarbonyl)ethyl]aniline (**2**) as a product of double addition of methyl acrylate to aniline has also been observed as a by-product over H-BEA and H-FAU catalysts. The influences of the reaction parameters such as temperature and catalyst amount, and type of α,β-unsaturated esters and amines have been also investigated.

KEY WORDS: zeolite; hydroamination; methyl acrylate; aniline.

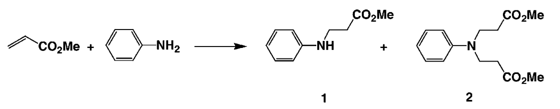
1. Introduction

As countless examples of nitrogen-containing organic molecules can be found in pharmaceutical, agricultural, and industrial areas, the synthesis of carbon–nitrogen bonds is of fundamental interest in organic chemistry. Among the numerous methods developed for the synthesis of nitrogen-containing building blocks such as amines, imines, and enamines, the most efficient and atom-economical method is the direct addition of amines to carbon–carbon double and triple bonds. Most of the studies are based on the addition of aniline or substituted anilines to aliphatic or aromatic alkynes [1]. This is probably related to lower Lewis basicity of the aniline nitrogen atom compared to aliphatic amine one. The lower Lewis basicity is a consequence of the mesomeric effect between the amine lone-pair and the phenyl group. Recently, there have been several reports on the hydroamination of aniline catalyzed by transition metals such as palladium [2–4], ruthenium [5], nickel [6], and rhodium [7]. It was also possible to perform the hydroamination of acrylic acid derivatives with cyclic amines [2,6,8–11].

To the present date, ion-exchanged BEA zeolite, Cu(I)/H-BEA, Rh(I)/H-BEA and Zn/H-BEA, have been reported as active catalysts for the heterogeneous hydroamination, such as the cyclization of 6-aminohex-1-yne and 3-aminopropylvinyl ether and the addition of aniline to phenylacetylene [12–15]. On the contrary, H-BEA was the most active catalyst for the hydroamination of 1,3-cyclohexadiene with aniline, while the incorporation of Zn^{2+} (Zn/H-BEA) led to the decrease of catalytic activity [16]. Recently, Halligudi and Shanbhag [17] reported the intermolecular hydroamination of phenyl acetylene with aniline over zinc exchanged montmorillonite clay.

The hydroamination of acrylate derivatives with amines is an attractive method for organic synthesis, since obtained products are important organic compounds or derivatives such as natural or unnatural amino acids. Heterogeneous catalysts have not been reported so far for the hydroamination of alkyl acrylates with amine, although homogeneous catalysis using transition metal complexes has been described in the literatures [2,6].

In this paper, we describe zeolites (BEA and FAU) as potential heterogeneous catalysts for the hydroamination of methyl acrylate with aniline (scheme 1). We also studied the hydroamination of some α,β-unsaturated esters with amines of different basicity.



(1)

2. Experimental

2.1. Catalyst preparation

Na-BEA ($SiO_2/Al_2O_3 = 33$, 67, 103)[1] were prepared by dry gel conversion (DGC) method [18]. H-BEA was obtained by the treatment of Na-BEA with NH_4NO_3 as follows: NH_4NO_3 (1.0 g) was dissolved in 50 ml of distilled water, and calcined Na-BEA (1.0 g) was added to the solution, and resulting mixture was stirred at 80 °C for 12 h. The procedure was repeated twice to obtain H-BEA zeolite. Finally, H-BEA zeolite was dried

---

*To whom correspondence should be addressed.
E-mail: sugi@apchem.gifu-u.ac.jp

[1] Numbers in parentheses show the SiO^2/Al_2O_3 ratio of the zeolites.

1011-372X/05/0800–0191/0 © 2005 Springer Science+Business Media, Inc.

for overnight at 150 °C. H-FAU ($SiO_2/Al_2O_3 = 5.6$; HSZ-320 HOA) and H-MOR ($SiO_2/Al_2O_3 = 24.6$; HSZ-650HOA) were obtained from Tosoh Corporation, Tokyo, Japan. H-FAU ($SiO_2/Al_2O_3 = 30$; CBV720) and H-BEA ($SiO_2/Al_2O_3 = 25$; CP 814B-25) were supplied from Zeolyst International, Valley Forge, PA, USA. Prior to use, all samples were calcined with the following calcinations program: room temperature to 550 °C (heating rate 1 °C/min), 550 °C for 7 h under air flow.

2.2. Catalyst characterization

X-ray diffractograms (XRD) were recorded on a Shimadzu XRD-6000 diffractometer with CuK_α radiation ($\lambda = 1.5418$ Å). The crystal size and morphology of the samples were observed by scanning electron microscopy (SEM) using a Philips XL30 microscope. Nitrogen adsorption–desorption isotherms were obtained at 77 K using a Belsorp 28SA apparatus (Bel Japan). Acidity measurements were performed by temperature programmed desorption of ammonia (NH_3-TPD) on a BEL TPD-66 apparatus (Bel Japan).

2.3. Hydroamination

In a typical reaction, catalyst (0.1 g) was suspended in toluene (4 ml), and amine (1 mmol) and methyl acrylate (2 mmol) were added to the suspension. The reaction mixture was heated to 100 °C with stirring for required time. After the reaction, liquid samples were analyzed by gas chromatography (Shimadzu GC-14B with HP Ultra-1 capillary column, 25 m) using dodecane as an internal standard. Products of the reaction were identified by GC-MS (Shimadzu MS-5000 with HP Ultra-1 capillary column, 25 m), and ^{1}H- and ^{13}C-NMR NMR spectra (JEOL α-400 FT-NMR spectrometer). The conversion was determined from the amount of consumed amine during reaction. Yields of products were calculated based on introduced amine and the selectivity based on consumed amine.

3. Results and discussion

3.1. Hydroamination over zeolites

The hydroamination of methyl acrylate with aniline was examined to study the catalytic properties of zeolites. Zeolites catalyzed the reaction to give mainly *anti*-Markovnikov adduct (*anti*-adduct), *N*-[2-(methoxycarbonyl)ethyl]aniline (**1**), of which structure was confirmed by ^{1}H- and ^{13}C-NMR spectra [2], and no Markovnikov adduct, *N*-[1-(methoxycarbonyl)ethyl]aniline (**3**), was detected by GC. However, *N,N*-bis[2-(methoxycarbonyl)ethyl]aniline (**2**), a product of the double addition of methyl acrylate to aniline, has been observed as a by-product (scheme 1).

Table 1 summarizes catalytic activity and yields of products of the hydroamination of methyl acrylate with aniline by zeolites. H-FAU and H-BEA zeolites with three-dimensional 12-membered pore system showed high catalytic activity for the hydroamination. H-FAU(5.6) was the most active catalyst for the hydroamination with aniline conversion 91% within 18 h reaction; however, catalytic activity was decreased to 57% by 18 h reaction by dealuminated H-FAU(30). Moreover, H-BEA(25) has also high activity in the similar level of H-FAU(5.6) (85% by 18 h reaction). However, one-dimensional 12-membered zeolites such as H-MOR(25) have only low activity: the conversion of aniline was 12%.

The formation of **2** has been observed as a product of double addition of methyl acrylate in the case of H-FAU(5.6) and H-BEA(25) zeolites. The yield of **2** was more significant for H-BEA(25) (7.8% after 8 h and 16.6% after 18 h, respectively), whereas only negligible for H-FAU(30) (1.4% after 8 h and 2.8% after 18 h, respectively).

Catalytic activity of H-BEA with different SiO_2/Al_2O_3 molar ratio by DGC method in the hydroamination was examined to know the influence of acid amount of zeolites in the catalysis. As decrease of the acid amount with increasing SiO_2/Al_2O_3 molar ratio of

Table 1
The hydroamination of methyl acrylate with aniline over zeolites[a]

Zeolite	SiO_2/Al_2O_3	Conversion aniline (%)	Yield of products[b] (%)	
			1	**2**
H-FAU	5.6	91.0	82.1	8.9
	30	56.9	54.1	2.8
H-BEA	25	84.8	68.2	16.6
	33	68.8	64.0	4.8
	67	64.5	61.9	2.6
	103	61.8	59.3	2.5
H-MOR	25	12.4	12.4	0

[a] Reaction conditions: catalyst, 0.1 g; aniline, 1 mmol; methyl acrylate, 2 mmol, reaction temperature, 100 °C; time, 18 h; toluene, 4 ml.
[b] Reaction products were confirmed by ^{1}H-NMR, GC, and GC-MS. All of products were assigned as linear *anti*-Markovnikov adducts.

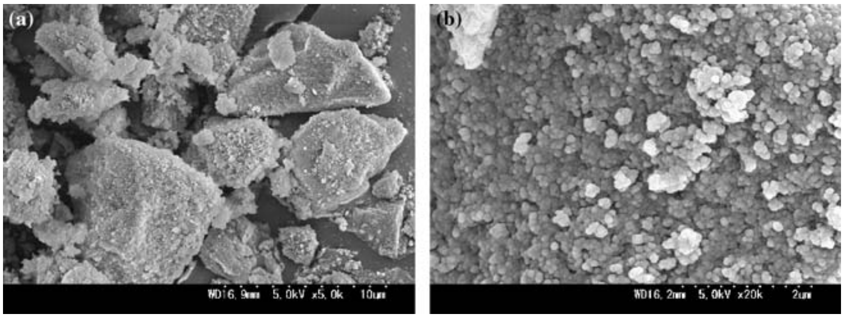


Figure 1. SEM images of zeolites. (a) H-BEA(30) by DGC method, and (b) commercial H-BEA(25) (CP814B-25).

H-BEA from 30 to 100 led to the decrease of aniline conversion and the yield of **1**: aniline conversion of 69% and **1** in yield of 64% was achieved for H-BEA(30), whereas aniline conversion of 62% and yield of **1** of 59% were observed for H-BEA(100). Nevertheless, the commercial H-BEA(25) from Zeolyst International has slightly higher activity than the other H-BEA zeolites, whereas **2** was formed in higher yield compared with H-BEA(30) by DGC method. The difference of particle size of the zeolites is one of reasons for the differences in catalytic activity: SEM images of H-BEA(30) by DGC method was observed as agglomerates of small particles around 0.1 μm; however, commercial H-BEA(25) has particle of ca. 1 μm with no agglomerates (figure 1).

3.2. *Effects of reaction parameters*

Figure 2 shows the influence of reaction temperature on catalytic activity and the yield of **1** over H-BEA(25). The activity was strongly affected by the increase of the temperature, whereas the yield of **1** was not significantly influenced. The conversion of aniline increased almost linearly with the temperature up to 100 °C, and no increase of the conversion was observed with further increase of temperature to 120 °C. The yield of **2** increased with increasing reaction temperature.

Effects of the catalyst amount on the hydroamination of methyl acrylate with aniline over H-BEA(25) are shown in figure 3. It seems that 0.1 g of the zeolite with 1 mmol of aniline is an optimal amount to achieve the satisfactory conversion of aniline. Increasing the amount of the catalyst up to 0.2 g resulted only in negligible increase both of the conversion and yields.

3.3. *Effects of type of amine*

The substituent group on aniline has strong influence on the basicity of corresponding aryl amine. Therefore, the hydroamination of methyl acrylate with *p*-substituted anilines and benzylamine has been studied over zeolites (table 2). More basic 4-anisidine and less basic 4-nitroaniline compared to aniline have been chosen as the reactants. Benzylamine with strongest basic properties has been included to this study. Table 2 summarizes the results of the catalytic activity of H-FAU(5.6) and H-BEA(25) in the hydroamination of methyl acrylate with 4-anisidine, 4-nitroaniline, and benzylamine. They gave the products corresponding to **1** and **2**. As for both H-FAU(5.6) and H-BEA(25), amine conversion decreases with basicity of amines. However, H-BEA(25) was more active than H-FAU(5.6). After 18 h, the amine conversion has achieved in 90–100% by using H-BEA(25), while only slight increase of the amine conversion by the use of H-FAU(5.6) has been observed (4-anisidine conversion increased about 10%, and benzyl amine conversion about 17% from 8 h to the 18 h reaction for H-FAU(5.6)). Prolonged reaction period resulted in the increase of amine conversion in the case of H-BEA(25). For example, the conversions of 4-anisidine and benzyl amine were enhanced to about 51% and 43%, respectively. In all the cases, the mono-adduct corresponding to **1** was predominantly formed over H-FAU(5.6) after 18 h, whereas the preferential formation of the di-adduct corresponding to **2** has been observed over H-BEA(25) zeolite with prolonged reaction period. Especially, in the case of benzylamine, the yield of *N,N*-bis[2-(methoxycarbonyl)ethyl]benzylamine was 56.5%

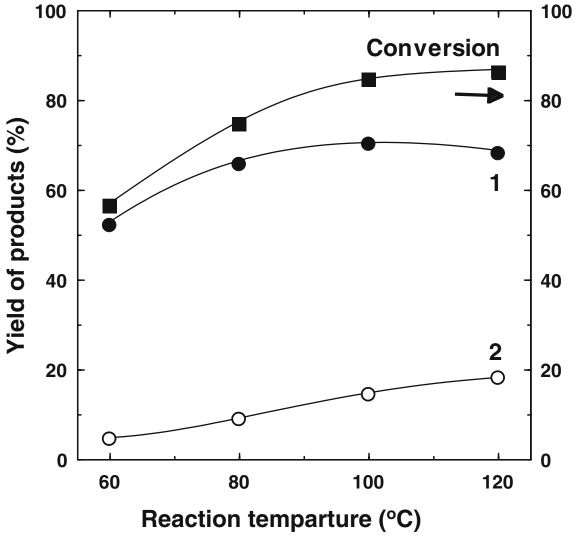


Figure 2. Influence of the temperature on the hydroamination of methyl acrylate with aniline over H-BEA ($SiO_2/Al_2O_3 = 25$). Reaction conditions: catalyst, 0.1 g; aniline, 1 mmol; methyl acrylate, 2 mmol; solvent: toluene, 4 ml; period, 18 h. Legends: (■) aniline conversion, (●) **1**, and (▼) **2**.

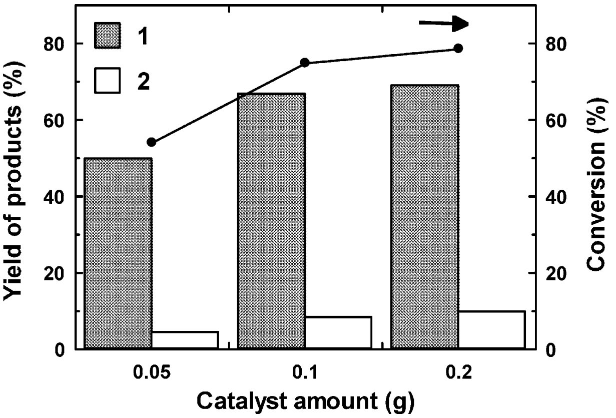
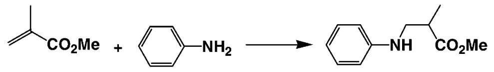


Figure 3. Effect of the catalyst amount on the hydroamination of methyl acrylate with aniline over H-BEA ($SiO_2/Al_2O_3 = 25$). Reaction conditions: catalyst, H-BEA(25); aniline, 1 mmol; methyl acrylate, 2 mmol; solvent: toluene, 4 ml; reaction temperature, 100 °C; reaction period, 8 h.

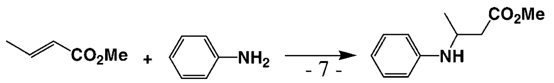
after 18 h reaction for H-BEA(25) compared with 10.6% for H-FAU(5.6). It suggests that an appropriate acid amount and strength of H-BEA(25) as well as its structure enables the double addition of the methyl acrylate to the amine because the nucleophilicity of nitrogen of amine decreased by the addition of methyl acrylate.

3.4. *Effect of substitution of methyl acrylate*

If the reaction over zeolite proceeds *via* cationic intermediate resulted from activation of olefin, it must eventually obey Markovnikov law. However, the hydroamination of methyl acrylate with various amines, discussed above, shows the preferential formation of *anti*-adduct in all cases.



3 (2)



4 (3)

The hydroamination of methyl methacrylate and methyl crotonate with aniline was investigated over H-FAU(5.6) and H-BEA(25) to elucidate the mechanism (schemes 2 and 3). As shown in table 3, the hydroamination of methyl methacrylate with aniline over H-FAU(5.6) and H-BEA(25) gave *anti*-Markovnikov adduct (**3**) in 38% and 21% conversion, respectively, and the yield of Markovnikov adduct was negligibly low. Further, both H-FAU(5.6) and H-BEA(25) zeolite gave similar level of conversion (42% in H-FAU(5.6), 46% in H-BEA(25)) in the hydroamination of methyl crotonate with the formation of *anti*-Markovnikov adduct (**4**) in the yields of 41.2% and 41.6%, respectively. These results clearly show that hydroamination of α,β-unsaturated esters with aniline over the zeolites in current study proceeds *via* selective *anti*-Markovnikov addition. Recently, Li *et al.* [2] also reported that the homogeneous hydroamination of methyl methacrylate and methyl crotonate with piperidine gave predominantly *anti*-Markovnikov adducts.

3.5. *Mechanistic aspects of the hydroamination*

Anti-adduct **1** was also observed in the homogeneous hydroamination of aniline and methyl acrylate with cationic (diphosphine)Pd(II) complexes. The hydroam-

Table 2

Effects of type of amines over H-BEA(25) and H-FAU(5.6) catalysts in the hydroamination of methyl acrylate[a]

Amine	Zeolite (SiO_2/Al_2O_3)	Time (h)	Conversion amine (%)	Yield of products[b] (%)	
				Anti-adduct[c]	Di-adduct[d]
4-anisidine	H-BEA(25)	8	38.7	36.8	1.9
		18	90.4	69.9	14.7
4-anisidine	H-FAU(5.6)	8	55.1	49.3	5.1
		18	64.8	57.3	5.9
4-nitroaniline	H-BEA(25)	8	100	91.3	8.7
	H-FAU(5.6)	8	100	90.4	9.6
Benzylamine	H-BEA(25)	8	56.9	50.4	6.4
		18	100	39.9	56.5
Benzylamine	H-FAU(5.6)	8	68.3	55.5	10.0
		18	80.9	64.5	10.6

[a] Reaction conditions: catalyst, 100 mg; amine, 1 mmol; methyl acrylate, 2 mmol; reaction temperature, 100 °C, solvent: toluene, 4 ml.

[b] Estimated by GC. The structure of obtained products and their molecular weight were measured by ^{1}H-NMR and GC-MS, respectively.

[c] *Anti*-Markovnikov adduct assigned by ^{1}H-NMR and no branched adduct was detected by GC.

[d] Di-adducts were also assigned as di-linear product (di-*anti*-Markovnikov adduct) by ^{1}H-NMR. In the case of benzylamine, two isomers corresponding to di-adduct could be detected by GC-MS. One of them (major product) was assigned as di-linear product (di-*anti*-Markovnikov adduct) by ^{1}H-NMR; however, the other isomer could not be assignable due to its lower content.

Table 3

Effect of type of α,β-unsaturated esters over H-BEA(25) and H-FAU(5.6) catalysts in the hydroamination with aniline[a]

α,β-unsaturated esters	Zeolite (SiO_2/Al_2O_3)	Conversion aniline (%)	Yield of products[b] (%)	
			Anti-adduct[c]	Di[d]
Methyl acrylate	H-BEA(25)	84.8	68.2	16.6
	H-FAU(5.6)	91.0	82.1	8.9
Methyl methacrylate	H-BEA(25)	21.0	19.8	1.2
	H-FAU(5.6)	38.0	37.8	0.2
Methyl crotonate	H-BEA(25)	46.0	41.9	4.1
	H-FAU(5.6)	42.0	41.6	0.4

[a] Reaction conditions: catalyst, 100 mg; amine, 1 mmol; α,β-unsaturated ester, 2 mmol; reaction temperature, 100 °C, solvent: toluene, 4 ml.

[b] Estimated by GC. The structure of obtained products and their molecular weight were measured by ^{1}H-NMR and GC-MS, respectively.

[c] *Anti*-Markovnikov adduct ssigned by ^{1}H-NMR and no branched adduct was detected by GC.

[d] Di-adducts were also assigned as di-*anti*-Markovnikov product by ^{1}H-NMR.

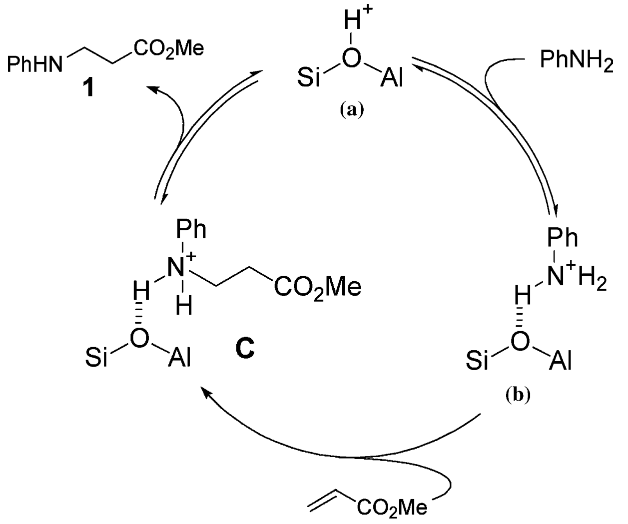


Figure 4. Proposed reaction mechanism of the hydroamination of methyl acrylate with aniline catalyzed by zeolites.

ination of aniline with methyl acrylate afforded *anti*-adduct **1** dominantly with homogeneous cationic (dppf)Pd(II) complex (dppf = 1,1′-bis(diphenylphosphino)ferrocene) as catalysts [2]. The catalysis proceeds by the σ-alkylpalladium complex following β-elimination to give an unstable palladium hydride complex [4]. Further, $Yb(OTf)_3$ catalyzed hydroamination of α,β-unsaturated esters with benzylamine also gave the *anti*-Markovnikov adducts *via* conjugate addition of amine [8–11]. However there are no reports to discuss the preferential formation of *anti*-Markovnikov adducts in hydroamination of α,β-unsaturated esters with amine.

We can show the probable path for the hydroamination of α,β-unsaturated esters with amine over zeolite catalysts in figure 4 as an example for aniline with methyl acrylate. The amine is activated on the acidic sites in the first step: aniline is adsorbed to the acidic site of zeolite (**A**) to form ammonium cation (**B**) by acid-base interaction, followed by Michael addition of methyl acrylate to give the mono-alanine ammonium intermediate (**C**). The intermediate (**C**), then, releases the *anti*-adduct **1** to regenerate acidic site of catalyst (**A**). The product **1** can be re-adsorbed to the catalyst generating the intermediate (**C**). Further addition of methyl acrylate with the intermediate (**C**) affords **2** with regeneration of active catalyst acidic site (**A**).

There is also another probable path for the hydroamination including the activation of methyl acrylate on acidic site in the first step: methyl acrylate is adsorbed at acidic site of zeolite catalyst followed the formation of corresponding cation. As in this mechanism, unfortunately, nucleophilic attack of aniline occurs preferentially to the α-carbon of methyl acrylate to give Markovnikov adduct. Similar mechanism has been proposed for the hydroamination of aniline with transition metal complexes [19,20], and for the hydroamination of 1,3-cyclohexadiene catalyzed by H-BEA catalyst [16].

It seems that figure 4 is the reasonable mechanism for predominant formation of an *anti*-Markovnikov adduct over zeolite catalyst, because the adsorption of aniline to active acidic site of zeolite with acid-base interaction is more appropriate than that of methyl acrylate to yield acrylate cation. Michael addition is also responsible for the preferential formation of *anti*-Markovnikov adduct. The selective formation of *anti*-Markovnikov adducts in the hydroamination of methyl methacrylate and crotonate supports that the formation of the intermediate (**C**) is key step for the hydroamination.

4. Conclusions

H-zeolites with 12-membered three-dimensional pore system, such as H-BEA and H-FAU, showed high catalytic activity for the hydroamination of methyl acrylate with aniline. *N*-[2-(methoxycarbonyl)ethyl]aniline (**1**) was formed as a main product, and *N,N*-bis[2-(methoxycarbonyl)ethyl]aniline (**2**), a product of the double addition of methyl acrylate to aniline, has been observed as a by-product. Both **1** and **2** are *anti*-Markovnikov adducts. Reaction temperature, catalyst amount, and particle size of zeolite influence the catalytic activity, whereas the yields of products of mono and double addition depend on the acidities and structures of used zeolites. The addition of methyl acrylate to *p*-substituted anilines and benzylamine also gave the adduct corresponding to **1** over H-BEA and H-FAU zeolites, and the products of double addition of methyl acrylate has been observed over H-BEA(25) with prolonged reaction time. The hydroamination of methyl methacrylate and crotonate with aniline over H-FAU(5.6) and H-BEA(25) also gave preferentially *anti*-Markovnikov adducts. It seems that the suitable acidity, structure, and particle size of zeolite accomplish the high conversion of amines in these hydroaminations.

Further aspects of the catalysis are under investigations, and will be published in near future.

Acknowledgements

A part of this work was financially supported by a Grant-in Aid for Scientific Research (B) 15350093, the Japan Society for the Promotion of Science (JSPS). J. Horniakova is grateful to JSPS for the postdoctoral fellowship.

References

[1] F. Pohlki and S. Doye, Chem. Soc. Rev. 32 (2003) 104.
[2] K. Li, P.N. Horton, M.B. Hursthouse and K.K. Hii, J. Organomet. Chem. 665 (2003) 250.
[3] R.Q. Su and T.E. Müller, Tetrahedron 57 (2001) 6027.
[4] J.J. Bozell and L.S. Hegedus, J. Org. Chem. 46 (1981) 2561.
[5] H. Schaffrath and W. Keim, J. Mol. Catal. A: Chem. 168 (2001) 9.
[6] L. Fandini and A. Togni, Chem. Commun. (2003) 30.
[7] C.G. Hartung, A. Tillack, H. Trauthwein and M. Beller, J. Org. Chem. 66 (2001) 6339.
[8] G. Jenner, Tetrahedron Lett. 36 (1995) 233.
[9] G. Jenner, Tetrahedron 43 (1996) 13557.
[10] J. d'Angelo and J. Maddaluno, J. Am. Chem. Soc. 108 (1986) 8112.
[11] S. Matsubara, M. Yoshioka and K. Utimoto, Chem. Lett. (1994) 827.
[12] J. Penzien, T.E. Muller and J.A. Lercher, Micropor. Mesopor. Mater. 48 (2001) 285.
[13] J. Penzien, C. Haeßner, A. Jentys, K. Köhler, T.E. Müller and J.A. Lercher, J. Catal. 221 (2004) 302.
[14] J. Penzien, T.E. Müllar and J.A. Lercher, Chem. Commun. (2000) 1753.
[15] J. Penzien, R.Q. Su and T.E. Müllar, J. Mol. Catal. A: Chem. 182–183 (2002) 489.
[16] O. Jimenez, T.E. Müller, W. Schwieger and J.A. Lercher, in: *Proceedings of the 14th International Zeolite Conference* (25–30 April, 2004, Cape Town, South Africa, 2788).
[17] G.V. Shanbhag and S.B. Halligudi, J. Mol. Catal. A: Chem. 222 (2004) 223.
[18] P.R. Hari Prasad Rao, K. Ueyama and M. Matsukata, Appl. Catal. A: Gen. 166 (1998) 97.
[19] O. Löber, M. Kawatsura and J.F. Hartwig, J. Am. Chem. Soc. 123 (2001) 4366.
[20] O. Löber, M. Kawatsura and J.F. Hartwig, J.Am.Chem.Soc. 122 (2000) 9546.