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An Improved Asymmetrically-Modified Nickel Catalyst Prepared from Ultrasonicated Raney Nickel

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The ultrasonic irradiation of Raney nickel catalyst in water followed by the removal of the resulting turbid supernatant gave an excellent nickel catalyst (RNi-U) which generated an asymmetrically-modified nickel catalyst. An EPMA (SEM-EDX) study indicated that RNi-U consisted of a fairly pure nickel surface of homogeneous size. Tartaric acid–NaBr-modified RNi-U (TA–NaBr–MRNi-U) showed a high enantio-differentiating ability as well as reactivity in the hydrogenation of prochiral ketones such as 1,3-diones and 3-oxoalkanoic acid esters.

An asymmetrically-modified Raney nickel catalyst (MRNi) which can easily be prepared by soaking Raney nickel catalyst (RNi) in an aqueous solution of (*R*,*R*)- or (*S*,*S*)-tartaric acid (TA), is unique heterogeneous catalyst for the enantio-differentiating hydrogenation of prochiral ketones to the corresponding chiral alcohols. Intensive studies on the improvement of the asymmetrically-modified nickel catalyst and understanding of the hydrogenation mechanism over this catalyst have been carried out by us,[1)] Klabunovskii et al.,[2)] Sachtler et al.,[3)] and Imanaka et al.[4)] A series of these investigations have predicated that the hydrogenation-active sites of MRNi consist of enantio-differentiating (e.d.) sites to give an optically active product by the aid of adsorbed tartaric acid and non-enantio-differentiating (n.e.d.) sites to give a racemic product. It is also predicted that pure crystalline nickel surfaces can provide e.d. sites and disordered nickel surfaces containing residual aluminum compounds work as n.e.d. sites. It was also reported that the modification of nickel with the sodium salt of TA gave a good catalyst for enantio-differentiation, but modification with free TA, or the Li, K, Mg, or Al salt of TA gave a catalyst that showed no effective enantio-differentiation.[1)] Thus, the adsorbed TA on the nickel surface was considered to provide the e.d. site only when it existed as a monosodium or disodium salt. The RNi catalyst treated twice with a large amount of a slightly acidic hot aqueous solution of tartaric acid, NaOH, and NaBr (TA–NaBr–MRNi) has been utilized up to this time as the best catalyst. This catalyst was developed following the idea that the n.e.d. site is expected to be chemically sensitive, so that it can be removed chemically at least in part by acid-corrosion and the rest of the sites can be deactivated by partial poisoning with adsorbed NaBr.[5)] Although TA–NaBr–MRNi showed fairly good enantio-differentiating ability, the hydrogenation activity and durability were not satisfactory especially in the hydrogenation of 1,3-diketones.[6)] Now this problem has been satisfactorily solved by the introduction of ultrasound irradiation in the preparation process of RNi.[7)] In the present paper, we wish to report our recent work to prove the functions of the ultrasound irradiation technique which enabled us to obtain MRNi with an excellent hydrogenation activity as well as a high enatio-differentiating ability.

Experimental

The scanning electron micrographs (SEM) and energy dispersive X-ray microanalysis (EDX) data were obtained with an assembly consisting of a Hitachi S-800 and a Horiba-EMAX-200 instrument. The beam voltage was 5 kV for SEM and 20 kV for EDX. From the peak height of Al–*Kα* and Ni–*Kα* in EDX, the relative aluminum content of local spots was determined. Powder X-ray diffraction spectra were taken with a Mac Science XP_{18} instrument with Cu–*Kα* radiation. The quantitative analyses of Ni^{2+} and Al^{3+} in the aliquots obtained by the digestion of the particles in the supernatant with nitric acid were carried out by EDTA titration. The ^1H NMR spectra were taken with a JEOL GX-400 spectrometer. The optical rotation was measured with a Perkin–Elmer 243b polarimeter. Analytical GLC was carried out with a Shimadzu GC-14A instrument equipped with a 30 m silica capillary column coated with PEG-20M. Preparative GLC was carried out with a Shimadzu 5A instrument using a 6 m×6 mm o.d. stainless steel column packed with 15% NPGS on Chromosorb W. Preparative MPLC was carried out with a Lobar column (Lichroprep-Si 60, Merck) using a Waters R-403 refractometer as a detector.

Raney alloy was courteously supplied by Kawaken Fine Chemical Co. Pure nickel powder (HNi) was prepared by the hydrogenolysis of well pulverized NiO by the reported method.[8)]

All chemicals except those listed below were obtained from commercial sources. Methyl 3-oxodecanoate, methyl 3-oxododecanoate, and methyl 3-oxotetradecanoate were prepared from 2,2-dimethyl-1,3-dioxane-4,6-dione and heptanoyl chloride, nonanoyl chloride, and undecanoyl chloride, respectively, by a reported method.[9)] 2,6-Dimethyl-3,5-heptanedione was obtained by the reaction between methyl 2-methylpropionate and 3-methyl-2-propanone.[10)]

Ultrasonicated RNi (RNi-U). RNi (W-1 type) was prepared from 38 g of Raney alloy (Ni/Al=42/58). The resulting RNi freed from NaOH and 400 ml of deionized water in a flask was subjected to ultrasonic irradiation in a bath type ultrasound generator (Honda 118 W) at 48 kHz for 3 min and the turbid supernatant suspension was removed by decantation from the paramagnetic nickel powders fixed with a magnet. The same operation was repeated another two times to afford RNi-U. The particles in the supernatant suspension for the analysis were collected from the combined supernatant by centrifuging. From 38 g of Raney alloy, 69 mg of the particles were obtained (ca. 0.3% of the RNi catalyst was obtained).

Ultrasonicated HNi (HNi-U). HNi (2 g) in 40 ml deionized water was subjected to ultrasonic irradiation by the same procedure as above.

Modifying Solution. (*R*,*R*)-Tartaric acid (24 g) and NaBr (240 g) were dissolved in water (2400 ml), and the pH of the solution was adjusted to 3.2 by the addition of 1 M NaOH (1 M=1 mol dm^{-3}). The resulting solution was heated in boiling water.

Tartaric Acid–NaBr-Modified RNi-U (MRNi-U). A half portion of the hot modifying solution was poured on the RNi-U prepared previously. After maintaining the mixture at 100 °C for 30 min, the supernatant solution was removed by decantation and the catalyst was washed with 200 ml of water. This catalyst was again immersed in the other portion of the modifying solution under the same conditions as before. Removal of the supernatant and successive washing with two 200 ml portions of water, two 200 ml portions of methanol, two 200 ml portions of THF, and three 200 ml portions of the solvent employed for hydrogenation gave a suspension of TA–NaBr–MRNi-U ready to be used for hydrogenation.

Tartaric Acid–NaBr-Modified RNi (MRNi). This catalyst was prepared by the same procedure as mentioned above except for the use of the conventional RNi (W-1 type) instead of RNi-U.

RNi Ultrasonicated at the Modification Step ([Ta–NaBr–MRNi]-U). This catalyst was prepared by the same procedures as in the case of MRNi except for the ultrasonic irradiation at the second modification step.

Tartaric Acid–NaBr-Modified HNi and HNi-U (MHNi and MHNi-U). These catalysts were obtained by the same modification procedure as in the case of RNi.

Hydrogenation. Hydrogenation of prochiral ketone was carried out in an autoclave by the reported procedures[1] under the conditions stated in the text.

Analysis of Hydrogenation Products. The hydrogenation products of methyl 3-oxoalkanoates were chemically pure methyl 3-hydroxyalkanoates isolated by distillation under reduced pressure. The e.e. of methyl 3-hydroxybutanoate was determined by polarimetry; $[\alpha]_{\text{D}}^{20}=-22.4°$ (neat) for optically pure methyl (*R*)-3-hydroxybutyrate. The e.e.s of the other methyl 3-hydroxyalkanoates were determined by ^{1}H NMR spectroscopy with a chiral shift reagent. The hydrogenation products of the 1,3-diones (**1**) were a mixture of (R^*, S^*)-diol (**3**), (R^*, R^*)-diol (**4**), and a small amount of half hydrogenated product (**2**). The ratio of each component was determined by gravimetry after separation with MPLC. The e.e.s of the (R^*, R^*)-diols were determined by polarimetry; $[\alpha]_{\text{D}}^{20}=-54.7°$ (*c* 10, MeOH) for optically pure (*R*,*R*)-2,4-pentanediol and $[\alpha]_{\text{D}}^{20}=-64.5°$ (*c* 1.0, MeOH) for optically pure (*S*, *S*)-2,6-dimethyl-3,5-heptanediol. Optically pure (*R*,*R*)-2,4-pentanediol and (*S*,*S*)-2,6-dimethyl-3,5-heptanediol were obtained by the crystallization of the corresponding hydrogenation products form diethyl ether or diisopropyl ether at −10 °C.[6]

Results and Discussion

Ultrasonic irradiation has frequently been employed in chemistry to homogenize samples or smash off fragile matters adhered to a solid. The present study is based on the idea that treatment of RNi by ultrasound prior to modification could smash off n.e.d. sites selectively from the catalyst's surface, since the n.e.d. sites, which consist of the aluminum enriched disordered nickel domain, are expected to be more fragile than the crystalline e.d. sites. To prove this prediction, EPMA (SEM-EDX) studies of the original RNi, RNi-U, particles in the supernatant, and TA–NaBr–MRNi-U were carried out. The results are shown in Fig. 1.

In the original RNi (Fig. 1 A), small particles (less than 1 μm) and large particles (10—20 μm) make aggregate-like clusters and the EPMA data indicate that the former contains more aluminum than the latter. Ultrasonic irradiation crushed the clusters and reduced a certain amount of unfavorable small particles. Thus, the resulting RNi-U consisted of relatively large particles with smooth pure Ni surfaces (Fig. 1 B). The powdered X-ray diffraction spectra of RNi and RNi-U showed identical patterns. There were no significant differences of half breadths in the peak at $2\theta=4.46$[Ni(111)] between RNi and RNi-U. This indicated that the ultrasonic irradiation did not change the crystalite size of the nickel particles grown in the alloy digestion process.

The solid materials collected form the supernatant by centrifugation (Fig. 1 C) are a mixture of small particles (less than 1 μm) and rather larger particles (5—10 μm) of flat plates with rough surfaces. The latter is expected to fall in flakes from the RNi surface. Both particles contain large amounts of aluminum. The treatment of these particles with diluted nitric acid gave a white insoluble part and a greenish acid-soluble part of which the $\text{Al}^{3+}/\text{Ni}^{2+}$ ratio was ca. 70/30. Powdered X-ray diffraction showed that the insoluble part was almost pure α-Al_2O_3. The total aluminum content of the particles in the supernatant was estimated to be ca. 85%. These results clearly demonstrated that ultrasonic irradiation removed the aluminum enriched part of RNi giving a clean nickel surface favorable for asymmetric modification.

On the first treatment with a slightly acidic tartaric acid–NaBr solution in the modification step, the remaining aluminum contaminant on the nickel surface was dissolved together with some amount of nickel by acid corrosion. On the second modification process, mono- and disodium tartarate settled on the remaining clean nickel surface. The EPMA data of the resulting TA–NaBr–MRNi-U (Fig. 1 D) showed that the population of small particles and the aluminum content in the

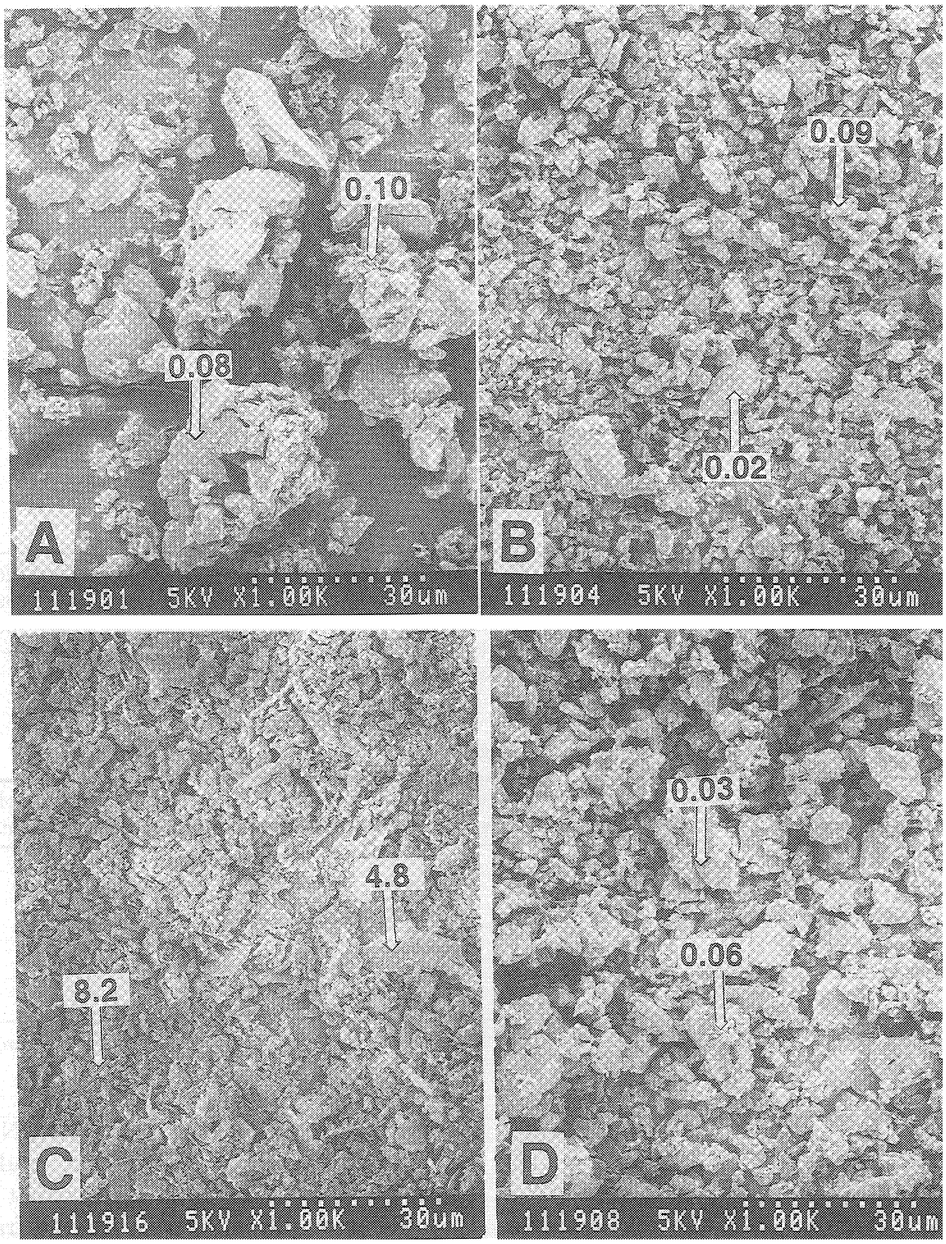
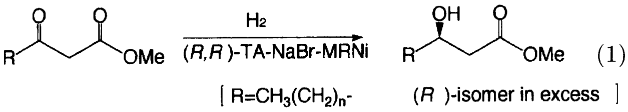


Fig. 1. SEM photograph and EDX data of RNi (A), RNi-U (B), materials in supernatant (C), and TA–NaBr–MRNi-U (D); figures in the photograph are ratio of peak height (Al–$K\alpha$/Ni–$K\alpha$) at the point indicated by an arrow.

particles were significantly reduced. Thus, TA–NaBr–MRNi-U is expected to consist of tough particles of almost pure nickel surface where tartaric acid provides the e.d. sites as the mono- or disodium salt.

The performance of the resulting MRNi-U was examined in the hydrogenations of methyl 3-oxoalkanoate (Eq. 1) and 1,3-dione (Eq. 2) in terms of the hydrogenation activity and enantio-differentiating ability, respectively.



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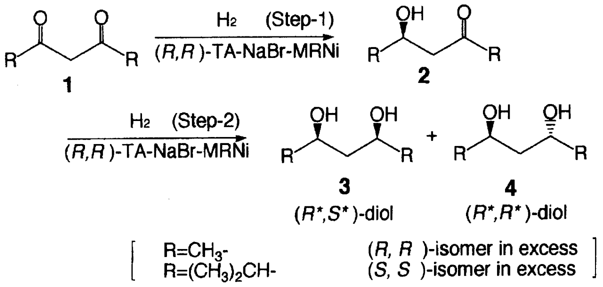

(2)

The results of the hydrogenation of a series of methyl 3-oxoalkanoates over the new MRNi-U are shown in

Table 1. Enantio-Differentiating Hydrogenation of Methyl 3-Oxoalkanoates

No.	Substrate $R-CO-CH_2-COOMe$	Catalyst	Reaction condition[a)]	Reaction time (h)	e.e. of the product (%)
1	$R=CH_3$	TA–NaBr–MRNi-U	A	2.5	86
2		TA–NaBr–MRNi	A	5.0	80
3		TA–NaBr–MRNi-U	B	3.0	86
4		TA–NaBr–MRNi-U	C	12	81
5		[TA–NaBr–MRNi]-U	A	3.0	60
6		TA–NaBr–MHNi	A	20	81
7		TA–NaBr–MHNi-U	A	20	81
8	$R=CH_3CH_2$	TA–NaBr–MRNi-U	A	4	92
9	$R=CH_3(CH_2)_6$	TA–NaBr–MRNi-U	A	36	89
10		TA–NaBr–MRNi	A	144	83
11	$R=CH_3(CH_2)_8$	TA–NaBr–MRNi-U	A	48	91
12		TA–NaBr–MRNi	A	192	86
13	$R=CH_3(CH_2)_{10}$	TA–NaBr–MRNi-U	A	48	94
14		TA–NaBr–MRNi	A	192	86

a) Reaction conditions; A; substrate (10 g): catalyst (1.9 g): solvent (methyl propionate, 20 ml, AcOH, 0.2 ml): initial pressure of H_2 100 kg cm^{-2}: temperature 100 °C. B; substrate (200 g): catalyst (19 g): solvent (methyl propionate, 200 ml, AcOH, 2 ml): initial pressure of H_2 100 kg cm^{-2}: temperature 100 °C. C; substrate (10 kg): catalyst (190 g): solvent (methyl propionate, 10 ℓ, AcOH, 15 ml): initial pressure of H_2 100 kg cm^{-2}: temperature 100 °C.

Table 2. Enantio-Differentiating Hydrogenation of 1,3-Diketones

No.	Substrate $R-CO-CH_2-CO-R$	Catalyst	Reaction time (h)	Composition of reacion product (**1**/**2**/**3**/**4**)	e.e. of **4** in the product (%)	Isolation yield of oprically pure **4** (%)
1	$R=CH_3$	TA–NaBr–MRNi-U	4	0/ 7/ 7/86	91	60
2		TA–NaBr–MRNi	24	0/20/10/70	90	21
3		TA–NaBr–MRNi	36	0/ 0/13/86	86	41
4	$R=(CH_3)_2CH$	TA–NaBr–MRNi-U	60	0/ 6/22/72	90	59
5		TA–NaBr–MRNi	192	1/17/16/66	85	32

Reaction condition; substrate (100 g); solvent (THF, 100 ml; AcOH 2 ml); catayst (19 g); initial H_2 (100 kg cm^{-2}); temperature 100 °C.

Table 1, together with the results obtained by using traditional MRNi as a reference. In comparison with the traditional catalyst, the new catalyst shortened the reaction time by a factor of 2 to 4 and resulted in a 5 to 8% increment of the optical yield. The highest optical yield (94%) was attained in the case of methyl 3-hydroxytetradecanoate (Table 1, No. 13). In the hydrogenation of methyl 3-oxobutanoate, the new catalyst proved to be useful for large scale hydrogenations carried out at a low catalyst/substrate ratio (Table 1, No. 4). It is noted that ultrasonic irradiation of RNi should be carried out before the modification process. When RNi in the modifying solution was subjected to ultrasonic irradiation, the resulting catalyst showed a poor enantio-differentiating ability (Table 1, No. 5). In this case, the modifying solution would be significantly contaminated with aluminum tartarate by the reaction between tartaric acid in the solution and aluminum enriched particles released from RNi by the ultrasonic irradiation. Thus the enantio-differentiating ability of the resulting catalyst was not good since the aluminum-tartarate adsorbed nickel surface could not function as an e.d. site. The use of HNi instead of RNi resulted in no significant change by the ultrasonic irradiation (Table 1, Nos. 6 and 7). This fact suggests that the ultrasound treatment is only effective with the fragile aluminum contaminated RNi.

MRNi-U was also found to be much more effective than traditional MRNi for the hydrogenation of symmetric 1,3-diones to a mixture of (R^*, S^*)-diols (**3**) and (R^*, R^*)-diols (**4**). The results are listed in Table 2. As shown in Eq. 2, the hydrogenation of 1,3-dione (**1**) proceeds in two steps via a half hydrogenated intermediate (**2**).[11)] The second step is much slower than the first step, especially in the reaction of 2,6-dimethyl-3, 5-heptanedione, and the reaction often stopped at the second step when using the traditional catalyst owing to insufficient catalytic activity and durability. The use of the new catalyst enabled us to overcome this problem. The reaction proceeded smoothly and was completed within a practical reaction time. The increment of the enantio-differentiating ability by the use of the new catalyst gave a hydrogenation product with a high content of **4** with a high e.e. and substantially increased the isolated yield of optically pure **4** from the hydrogenation product by recrystallization.

The results of the enantio-differentiating hydrogenation and those of the EPMA and powdered X-ray diffraction studies were very compatible and clearly indicated that the ultrasound treatment did not change the structure of the nickel particles but excluded the unfavorable parts form the crude RNi, and gave n.e.d. sites upon modification.

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