

# High durability of asymmetrically modified nickel catalysts prepared by in situ modification

Tsutomu Osawa<sup>a,\*</sup>, Saori Sakai<sup>a</sup>, Kazutomo Deguchi<sup>a</sup>,  
Tadao Harada<sup>b</sup>, Osamu Takayasu<sup>a</sup>

<sup>a</sup> Faculty of Science, Toyama University, Gofuku, Toyama 930-8555, Japan

<sup>b</sup> Faculty of Science and Technology, Ryukoku University, Seta, Otsu 520-2194, Japan

Received 27 December 2001; received in revised form 21 January 2002; accepted 13 March 2002

## Abstract

The in situ modification of a reduced Ni catalyst at the first run showed a high durability for the repeated use with high optical yields in the enantio-differentiating hydrogenation of methyl acetoacetate. Reduced Ni from Ni oxide and fine Ni powder were the best materials in comparison with Raney Ni. For attaining high optical yields and high durability, in situ modification and a Ni surface suitable for the enantio-differentiating hydrogenation are necessary. One of the reasons for the low durability of the conventional *pre*-modified Ni with repeated use would be the desorption of tartaric acid from the catalyst surface during the hydrogenation reaction. © 2002 Elsevier Science B.V. All rights reserved.

**Keywords:** Repeated use; In situ modification; Enantio-differentiating; Hydrogenation; Methyl acetoacetate

## 1. Introduction

The tartaric acid-NaBr-modified Raney Ni (TA-NaBr-MRNi) catalyst is one of the most successful enantio-differentiating heterogeneous catalysts. This catalyst was conventionally prepared by a *pre*-modification method. That is, RNi was immersed and modified in an aqueous solution containing TA and NaBr at 373 K before the hydrogenation process (this solution was adjusted to pH 3.2 in advance). This prepared TA-NaBr-MRNi hydrogenates various  $\beta$ -functionalized ketones [1,2] and 2-alkanones [3] in high optical yields. The highest optical yield of 98% was reported for the hydrogenation of methyl 3-cyclopropyl-3-oxopropionate [4]. Although the

*pre*-modification is very simple and the resulting catalyst gave a high enantio-selectivity, it has not been scaled up for industrial operation. One of the main reasons is the generation of a large amount of waste solution involving nickel ions during the *pre*-modification procedure [5]. Recently, we reported that the in situ modification (TA and NaBr were directly added to the reaction media in the first run) was applied to the enantio-differentiating hydrogenation of methyl acetoacetate resulting in ca. 80% optical yield over fine Ni powder (FNiP) and reduced Ni (HNi) catalysts [6,7]. This in situ modification generates no significant Ni ion waste during the entire process of the enantio-differentiating hydrogenation. Another disadvantage of the conventional *pre*-modified nickel catalyst is the lack of durability with repeated use. The enantio-differentiating ability of the conventional TA-NaBr-MRNi decreased to almost zero after three

\* Corresponding author. Fax: +81-76-445-6549.

E-mail address: osawa@sci.toyama-u.ac.jp (T. Osawa).

successive hydrogenation runs of methyl acetoacetate [8]. The hydrogenating ability also decreased after the three runs. An improvement in the durability of the conventional pre-modified Ni catalyst was reported by Tai and co-workers. They reported that the treatment of the tartaric acid-NaBr-modified Ni with an amine, such as pyridine, improved the durability for repeated use. This pyridine/TA-NaBr-modified Ni attained 72–82% during 10 runs [9]. They also prepared a TA-NaBr-modified Ni catalyst embedded in silicone rubber. The durability with repeated use was significantly improved by the embedding. The optical yields were 70–75% during 27 repeated runs. However, these values were 10% lower than that of the first run over TA-NaBr-MRNi [8].

By using the in situ modification, we found that the durability of the catalyst with repeated use was significantly improved [10]. In the present paper, a highly durable catalyst is described for the enantio-differentiating hydrogenation of methyl acetoacetate over a FNiP and an HNi catalyst prepared by an in situ modification. The important factors for sustaining a high durability by the in situ modification for repeated use are also discussed.

## 2. Experimental

All the chemicals were used as received. The GLC measurement of the products was carried out using a Hitachi 263-30 gas chromatograph. The optical rotations were observed using a JASCO DIP-1000 polarimeter.

### 2.1. Catalyst

*FNiP catalyst.* Commercially available FNiP (0.5 g) (Vacuum Metallurgical, mean particle diameter: 20 nm) was treated in a hydrogen stream at 553 K for 0.5 h before use.

*HNi catalyst.* Commercially available nickel oxide (1.5 g) (Nacalai Tesque, lot M3F86790) was reduced in a hydrogen stream at 623 K for 1 h before use.

*RNi catalyst.* Raney nickel alloy (0.95 g) (Kawaken Fine Chemicals, Ni/Al = 42/58) was developed in a 20% NaOH solution at 373 K for 1 h. The catalyst was then washed 25 times with 10 cm<sup>3</sup> distilled water.

### 2.2. Enantio-differentiating hydrogenation using in situ modification

Methyl acetoacetate (5 g) was hydrogenated at 373 K over the activated Ni catalyst in tetrahydrofuran (THF) (10 cm<sup>3</sup>) solution with acetic acid (0.1 g) at the initial hydrogen pressure of 9 MPa. The hydrogenation was carried out in a glass tube (30 cm<sup>3</sup>) in an autoclave (100 cm<sup>3</sup>). The (*R,R*)-TA and NaBr were added to the reaction media only for the first run (the amounts of TA and NaBr are stated in the text). TA was dissolved in THF. NaBr was added as an aqueous solution of 50 mm<sup>3</sup> distilled water. After the reaction was completed, the reaction medium was separated by decantation from the catalyst and then subjected to distillation. The hydrogenation products obtained by simple distillations showed more than a 98% chemical purity (GLC analyses: 383 K, 5% Thermon 1000 on Chromosorb W). For the repeated use of the catalyst, the catalyst remaining in the glass tube after decantation was washed three times with 10 cm<sup>3</sup> of THF and then subjected to the next run under the same reaction conditions without TA and NaBr.

### 2.3. Enantio-differentiating hydrogenation using pre-modification

The HNi catalyst was immersed in an aqueous solution of (*R,R*)-TA and NaBr at 373 K for 1 h. The modification solution was adjusted to pH 3.2 using 1 mol dm<sup>-3</sup> NaOH solution in advance. The obtained tartaric acid-NaBr-modified HNi was used for the hydrogenation of methyl acetoacetate in a solution of THF with acetic acid. The conditions for the hydrogenation of the first run and the repeated runs were the same as those for the hydrogenation using in situ modification.

### 2.4. Determination of optical yield

The optical yield of the product was obtained using the following equation:

$$\text{optical yield (\%)} = \frac{[\alpha]_{\text{D}}^{20} \text{ of hydrogenation product}}{[\alpha]_{\text{D}}^{20} \text{ of optically pure methyl 3-hydroxybutyrate} \times 100}$$

The specific optical rotation of the optically pure (*R*)-methyl 3-hydroxybutyrate is  $-22.95^\circ$  (neat) [5].

### 3. Results and discussion

#### 3.1. Repeated use of a modified FNiP prepared by in situ modification

Fig. 1 shows the results of the optical yield during repeated runs of the in situ modified FNiP catalyst [10]. A 100 mg sample of (*R,R*)-TA and 2 mg of NaBr were added to the reaction media only during the first run. For the first to fourth runs, the optical yields remained at about 70%. When racemic sodium 2-ethylhexanoate was added to the reaction media in the fifth run, the optical yield increased to 80%. In runs 6–23, 80–85% optical yields were attained. In runs 24–26, 76–78% optical yields were produced. The addition of racemic sodium 2-ethylhexanoate to the reaction media in the 26th run increased the optical yield to 80% for the 27th run. These runs showed the remarkable durability of the catalyst for the enantio-differentiating hydrogenation of methyl acetoacetate. The addition of sodium 2-ethylhexanoate

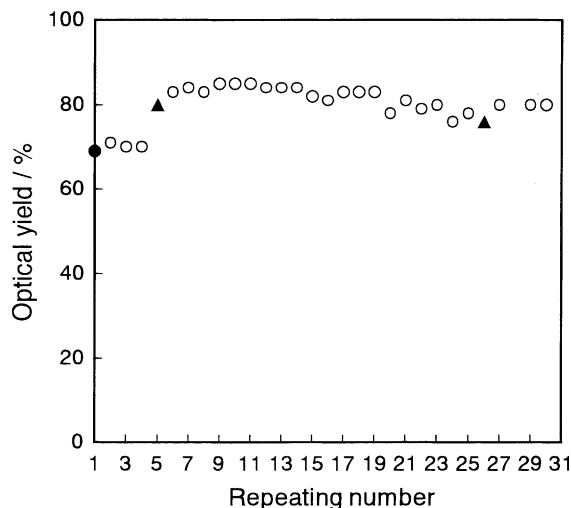


Fig. 1. Change in the optical yield with run number over the in situ modified FNiP for the enantio-differentiating hydrogenation of methyl acetoacetate: (●) addition of 100 mg of TA and 2 mg of NaBr to the reaction media; (▲) addition of 5 mg of sodium 2-ethylhexanoate to the reaction media.

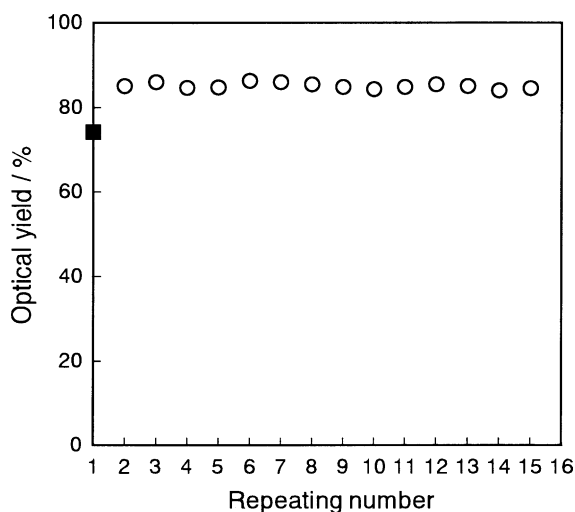


Fig. 2. Change in the optical yield with run number over the in situ modified FNiP for the enantio-differentiating hydrogenation of methyl acetoacetate: (■) addition of 100 mg of TA, 2 mg of NaBr, and 5 mg of sodium 2-ethylhexanoate to the reaction media.

increased the optical yield of the reaction. The hydrogenation was completed within 5 h for the first run, and within 2 h for each run from 2 to 30. No decrease in the hydrogenation activity was observed under the present experimental conditions during the repeated runs.

For attaining high optical yields from the first run, the addition of TA, NaBr, and sodium 2-ethylhexanoate in the first run would be more appropriate for the practical procedure of the enantio-differentiating hydrogenation of methyl acetoacetate. Fig. 2 shows the results of the repeated use of the modified FNiP prepared by in situ modification where (*R,R*)-TA, NaBr, and racemic sodium 2-ethylhexanoate were added to the reaction media during the first run. A 74% optical yield was attained for the first run. The optical yield increased in the second run and attained 84–86% for each of the runs 2–15.

#### 3.2. Repeated use of a modified HNi prepared by in situ modification

Fig. 3 shows the results of the repeated use of the HNi catalyst prepared by in situ modification. The optical yields of 87–89% were attained for each run from 2 to 9. The optical yield gradually decreased after the

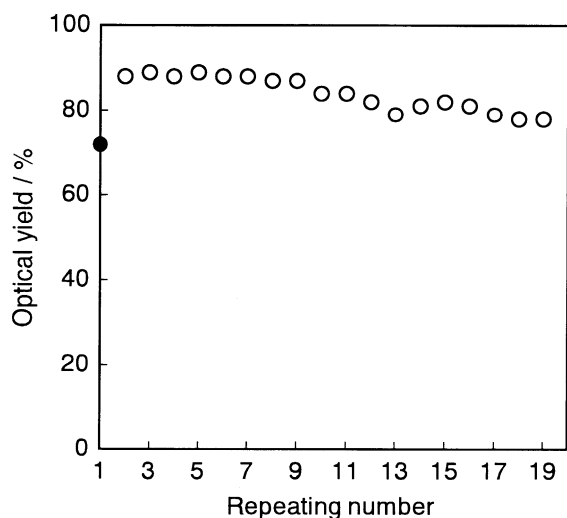


Fig. 3. Change in the optical yield with run number over the in situ modified HNi for the enantio-differentiating hydrogenation of methyl acetoacetate: (●) addition of 5 mg of TA and 0.8 mg of NaBr to the reaction media.

10th run, but 78% was maintained at the 19th run. These results indicated that TA and NaBr added to the reaction media during the first run would be firmly adsorbed onto the catalyst surface and create a highly durable enantio-differentiating surface. In the case of the repeated use of the HNi catalyst prepared by in situ modification, over 80% optical yields were attained without the addition of sodium 2-ethylhexanoate. We reported that the sodium ion was the important factor for attaining high optical yields for the TA modified Ni catalysts [2]. Sodium ions added as NaBr would be adequate for attaining high optical yields for the HNi catalyst. In contrast, FNiP would need more sodium ions as sodium 2-ethylhexanoate in addition to NaBr in the present experimental conditions. The slight decrease of the optical yield with an increase in repeating number using in situ modified HNi could be a slight desorption of sodium ions from the catalyst surface.

### 3.3. The important factors for the repeated use of the modified Ni catalyst

#### 3.3.1. Repeated use of a modified RNi catalyst prepared by in situ modification

In contrast with the pre-modified RNi where the optical yield decreased during the first three runs [8], a

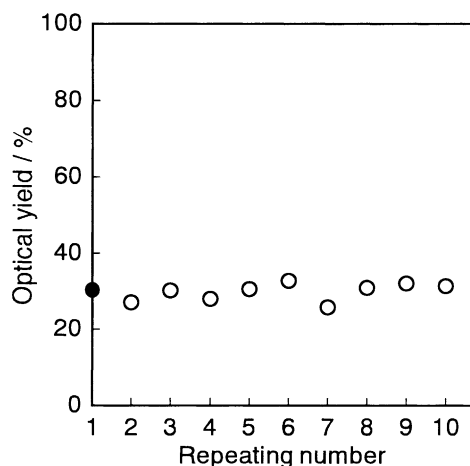


Fig. 4. Change in the optical yield with run number over the in situ modified RNi for the enantio-differentiating hydrogenation of methyl acetoacetate: (●) addition of 20 mg of TA and 1 mg of NaBr to the reaction media.

high durability with ca. 80–90% optical yield was attained by the in situ modified HNi catalyst. In order to clarify the factors responsible for the repeated use of the modified Ni catalyst, repeated use of a modified RNi catalyst prepared by in situ modification was investigated. Fig. 4 shows the results. The in situ modified RNi catalyst showed low optical yields of ca. 30%. However, these low optical yields were maintained during 10 runs. In contrast, the optical yields of the pre-modified RNi decreased to almost zero after three runs.

These results indicated that the in situ modification was a key method for improving the durability of the catalyst. However, the in situ modified RNi catalyst had greater durability but lower optical yield than the pre-modified catalyst. This would be because the surface of the RNi catalyst without the treatment of a TA solution had residual aluminum, which retarded the optical yield [11]. Therefore, for attaining high optical yields during repeated use, a Ni surface suitable for the enantio-differentiating hydrogenation as well as the in situ modification is necessary.

#### 3.3.2. Repeated use of a modified HNi catalyst prepared by pre-modification

Fig. 5 shows the durability after repeated use of the pre-modified HNi. The optical yields of the

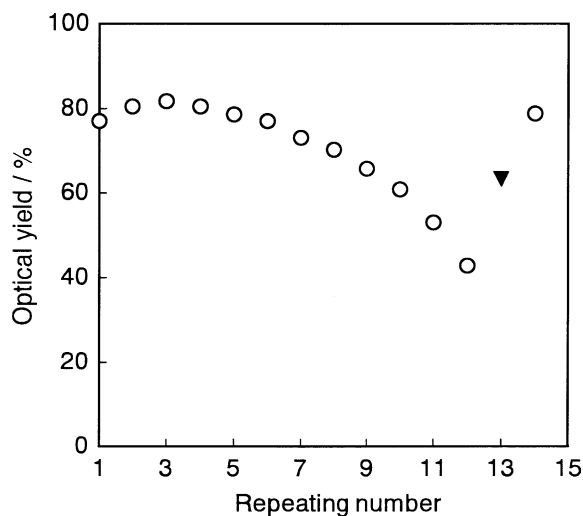


Fig. 5. Change in the optical yield with run number over the pre-modified HNi for the enantio-differentiating hydrogenation of methyl acetoacetate: (▼) addition of 2 mg of TA to the reaction media.

pre-modified HNi started to decrease after run 3 and reached 42% at run 12. Although the HNi has a suitable surface for the enantio-differentiating hydrogenation (regularly arranged Ni surface [12]), the optical yield of the pre-modified HNi decreased after repeated use. Therefore, both the in situ modification and a suitable Ni surface for the enantio-differentiating hydrogenation are very important factors for high optical yields with good durability.

In order to investigate the reason for the decrease in the enantio-differentiating ability of the pre-modified HNi after repeated use, 2 mg of TA was added to the reaction media at the 13th run in Fig. 5. The addition of TA increased the optical yield for the 13th run. The optical yield further increased to ca. 80% at run 14. This was comparable to the original enantio-differentiating ability of this catalyst. These results indicated that TA adsorbed on the Ni surface during the pre-modification would be gradually desorbed during the repeated use and that this caused a decrease in the optical yield. The lower durability of pre-modified RNi [8] than pre-modified HNi in the present work would also

be due to the easy desorption of TA from the RNi surface, because the surface of RNi would have Ni–Al compounds and have more amorphous Ni domain than HNi [12]. The high durability of the in situ modified Ni would be attributed to the stable adsorption of TA on the Ni surface.

#### 4. Conclusions

The combination of an in situ modification and a HNi produced a catalyst with a high durability and high optical yields during repeated use. FNiP and HNi were the best material in comparison to RNi. The in situ modification has a great advantage in not generating waste solution involving Ni ions, which are generated during the pre-modification process. The low durability of the conventional pre-modified Ni with repeated use would be caused by the desorption of TA from the catalyst surface during the hydrogenation reaction.

#### References

- [1] A. Tai, T. Harada, Tailored Metal Catalysts, Reidel, Dordrecht, 1986, p. 265 and references therein.
- [2] T. Osawa, T. Harada, O. Takayasu, Top. Catal. 13 (2000) 155, and references therein.
- [3] T. Osawa, T. Harada, A. Tai, Catal. Today 37 (1997) 465.
- [4] S. Nakagawa, T. Sugimura, A. Tai, Chem. Lett. (1997) 859.
- [5] T. Harada, M. Yamamoto, S. Onaka, M. Imaida, H. Ozaki, A. Tai, Y. Izumi, Bull. Chem. Soc. Jpn. 54 (1981) 2323.
- [6] T. Osawa, A. Ozawa, T. Harada, O. Takayasu, J. Mol. Catal. A 154 (2000) 271.
- [7] T. Osawa, Y. Hayashi, A. Ozawa, T. Harada, O. Takayasu, J. Mol. Catal. A 169 (2001) 289.
- [8] A. Tai, K. Tsukioka, Y. Imachi, Y. Inoue, H. Ozaki, T. Harada, Y. Izumi, in: Proceedings of the Eighth International Congress on Catalyst, Vol. 531, Berlin, Germany, 1984.
- [9] A. Tai, K. Tsukioka, H. Ozaki, T. Harada, Y. Izumi, Chem. Lett. (1984) 2083.
- [10] T. Osawa, S. Sakai, T. Harada, O. Takayasu, Chem. Lett. (2001) 392.
- [11] A. Tai, T. Kikukawa, T. Sugimura, Y. Inoue, S. Abe, T. Osawa, T. Harada, Bull. Chem. Soc. Jpn. 67 (1994) 2473.
- [12] Y. Nitta, F. Sekine, T. Imanaka, S. Teranishi, Bull. Chem. Soc. Jpn. 54 (1981) 980.