Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of the European Ceramic Society 24 (2004) 369–373
www.elsevier.com/locate/jeurceramsoc

Tribological properties of dimpled silicon nitride under oil lubrication

Y. Uehara[a], M. Wakuda[b], Y. Yamauchi[c], S. Kanzaki[c], S. Sakaguchi[c,*]

[a]Synergy Ceramics Laboratory, Fine Ceramics Research Association, Nagoya 463-8687, Japan
[b]Nissan Research Center, Nissan Motor Co., Ltd., Yokosuka 237-8523, Japan
[c]Synergy Materials Research Center, National Institute of Advanced Industrial Science and Technology, Nagoya 463-8687, Japan

Abstract

It is known that under lubricated conditions, dimpled surfaces can show improved tribological properties under planar/planar contact. This study investigates the effect of dimpling on the tribological properties of a silicon nitride ceramic against hardened bearing steel under oil lubricated, planar to curved surface contact conditions. Block-on-ring friction tests under oil lubrication were carried out over a range of sliding velocities, with a silicon nitride ceramic whose surface was dimpled by abrasive jet machining (AJM). The dimpled surface showed better tribological properties in terms of reduced friction coefficient compared with a lapped surface.

Keywords: Engine components; Finishing; Friction reduction; Si_3N_4; Surfaces; Wear; Lubrication

1. Introduction

Fine ceramics are being used for tribo-elements due to their superior mechanical properties such as high heat resistance, high wear resistance, lightweight, low thermal expansion and electric non-conductance, etc. In particular, silicon nitride is applied for automotive engine parts and bearings, for example as a cam follower, and some beneficial results having been reported.[1]

The reduction of friction of tribological components is considered to be necessary from a point of view of energy saving and environmental protection. Until now improvements in surface roughness of automotive parts, with the aim of reducing friction, have generally been achieved by grinding and lapping.[2,3] However, there is a limit in the achievable surface flatness and smoothness from a point of view of materials and processing.

Surface texturing is another method which has been researched for the reduction of friction of tribological components.[4,5] It is expected that the retention of lubricating oil in shallow pores textured on to the sliding surface will assist the formation of a lubricating film with resulting reduction of friction. Most of the previous research in this field has been carried out under planar-to-planar contact condition such as mechanical seals.[6,7] However, there is still limited research regarding the role of surface texturing under line contact conditions such as in journal bearings, and the effects remains unknown.

In this paper, in order to extend the applicable range of surface texturing, we report the effects on friction of a silicon nitride planar surface on to which textured dimples of various sizes have been produced.

2. Experimental procedure

2.1. Processing of surface textured dimples

The ceramic materials used were REFCERAM which is silicon nitride made in JFCC, fired with the sintering additives of 2.2 wt.% Magnesium (Mg) and 3.8 wt.% Cerium (Ce). Prior to surface texturing, the samples were ground into 3×4×2 mm blocks. The 3×4 mm surface of the samples was finished by lapping using first 3 μm and then 0.5 μm diamond pastes. The surface

* Corresponding author.
E-mail address: s.sakaguchi@aist.go.jp (S. Sakaguchi).

0955-2219/03/$ - see front matter
doi:10.1016/S0955-2219(03)00220-6

roughness following the lapping process was less than 0.01 μm Ra.

Subsequent micro-dimpling was performed by abrasive jet machining (AJM) using a masking film as shown in Fig. 1.[8] Micro dimples with a variety of dimensions and distributions were pattern machined on to the surface. The size of the dimples was set at 40, 80, or 120 μm in diameter and area densities of 7.5, 15, or 30%. The dimple depth was 5 μm for all the dimples. An example of the form of micro dimple is shown in Fig. 2.[9] The surface of the ceramic samples in the area around the dimples remained smooth. An example of the pattern of dimple is shown in Fig. 3.[9]

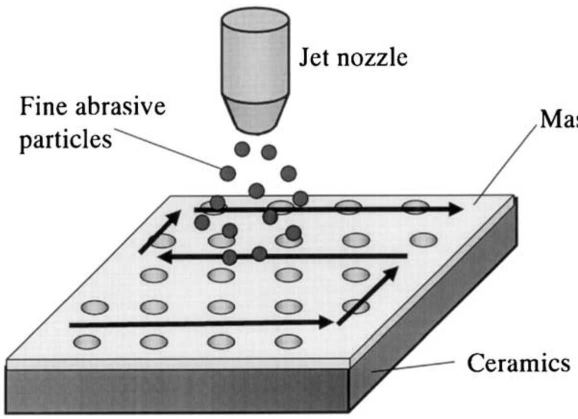

Fig. 1. Abrasive jet machining (AJM) process.

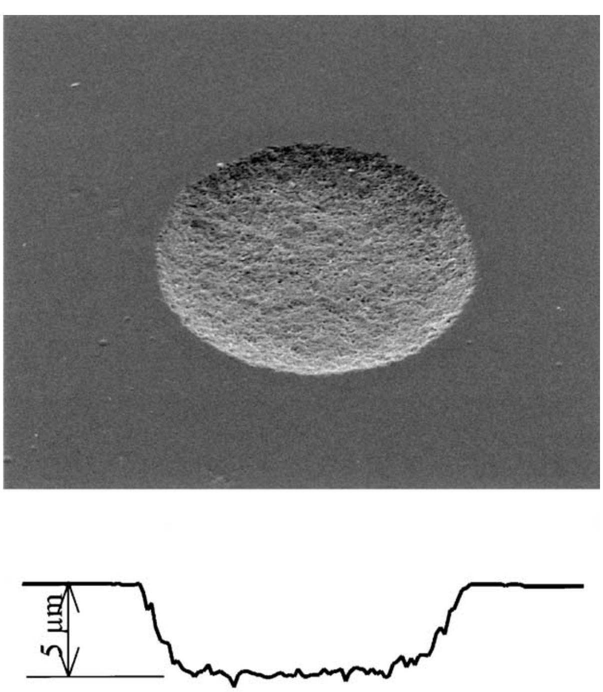

Fig. 2. Appearance of dimple produced by AIM process (diameter 40 μ m).

2.2. Friction testing method and test conditions

Friction tests were carried out using a block-on-ring method, which is shown Fig. 4. This testing method modeled line contact between the ring and the planar interface, such as is observed in journal bearings. The ring was made from hardened bearing steel, and the block was the silicon nitride whose surface was dimpled. The ring was 35 mm in radius and surface roughness was less than 0.1 μm Ra. A load was applied normally to the block, and during rotation of the ring, the friction generated in the tangentential direction was measured by a load cell attached behind the block. Friction coefficients were calculated using the load and this measured friction.

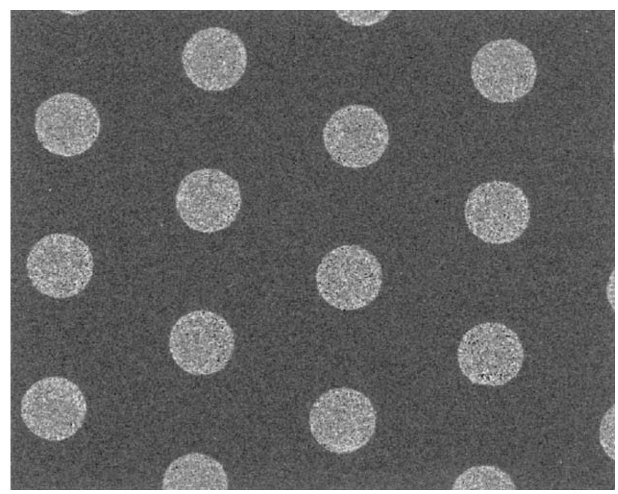

Fig. 3. Example of patterned dimple (dimple diameter 40 μm dimple density 15%).

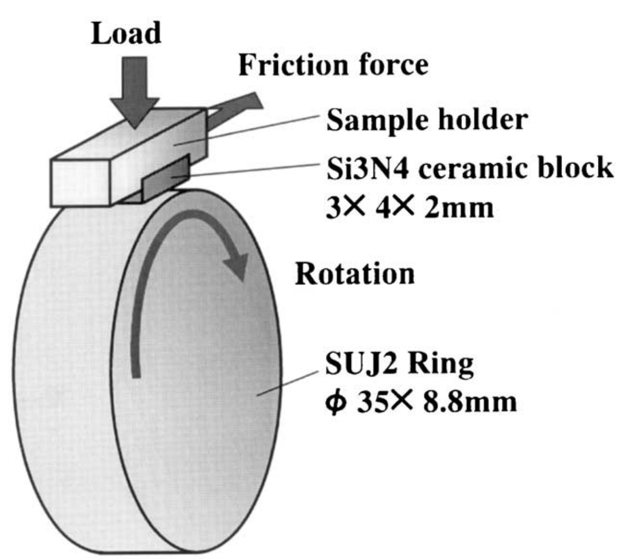

Fig. 4. Block-on-ring friction testing.

Friction test conditions are listed in Table 1. The load was 50 N, and sliding velocity was varied between 0.018–1.83 m/s. The contact pressure was calculated as 157 MPa for the 50 N load. The sliding contact zone was fully soaked in lubricant, ester basic oil, whose temperature was kept at 40 °C throughout the tests. The viscosity of lubricant oil was 0.012 Pa·s at the test temperature. In order to avoid initial unstable conditions, each friction test was carried out following a running-in operation with a load of 99 N, a sliding velocity of 0.018 m/s, and duration of 10 min.

3. Experimental results

The relationship between the sliding velocities and friction coefficients for the sample with no dimples is shown in Fig. 5. The friction coefficient was about 0.12 at the lowest sliding velocity, but decreased to about 0.05 at the highest sliding velocity, so it was estimated these test conditions represent mixed lubrication conditions.

The frictional properties of the samples with a dimple density of 7.5% are shown in Fig. 6 for different dimple sizes. Almost all the samples exhibited behavior similar to that of the non-dimpled surface.

The frictional properties of the samples with the 15% dimple density at different sizes are shown in Fig. 7. In the case of 40 and 80 μm dimples, friction coefficients reduced at the lower sliding velocities. In the case of 40 μm dimples, the friction coefficient was reduced by about 10% at low sliding velocities, although at high sliding velocity it became almost the same as the non-dimpled sample. For the 120 μm dimples, the friction coefficient was higher than the non-dimpled sample at all sliding velocities.

The frictional properties of the samples with the dimpled density of 30% at different sizes are shown in Fig. 8. At the lower sliding velocity, the dimpled samples all exhibited similar behavior, but at the higher sliding velocity, friction coefficients increased compared to the non-dimpled.

Table 1
Friction test conditions

Material	
Block	Silicon nitride (Referceram, JFCC)
Ring	Hardened steel (SUJ2)
Lubricant	Ester basic oil
Viscosity	0.012 Pa·s at 40 °C
Test condition	
Load	50 N
Sliding speed	0.018–1.83m/s
Temperature	40 °C

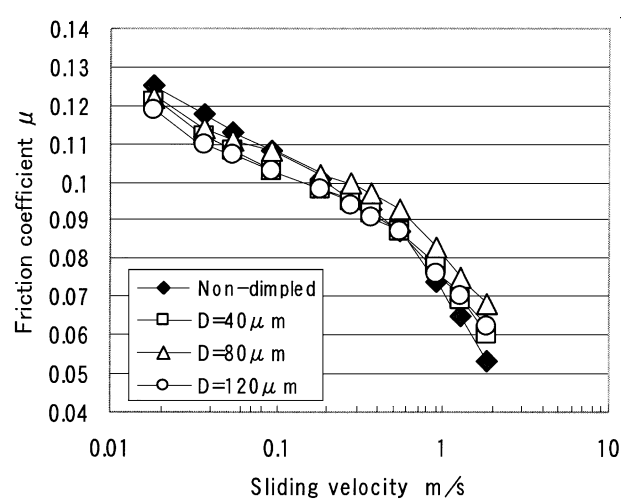

Fig. 6. Frictional properties of surfaces with 7.5% density dimples.

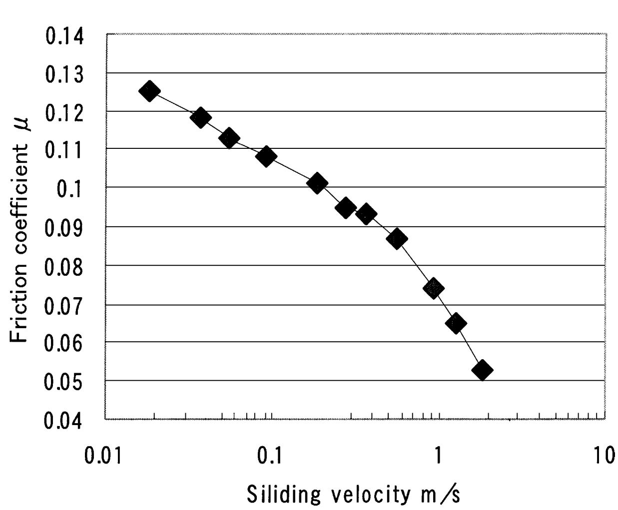

Fig. 5. Frictional properties of the lapped surface with no dimples.

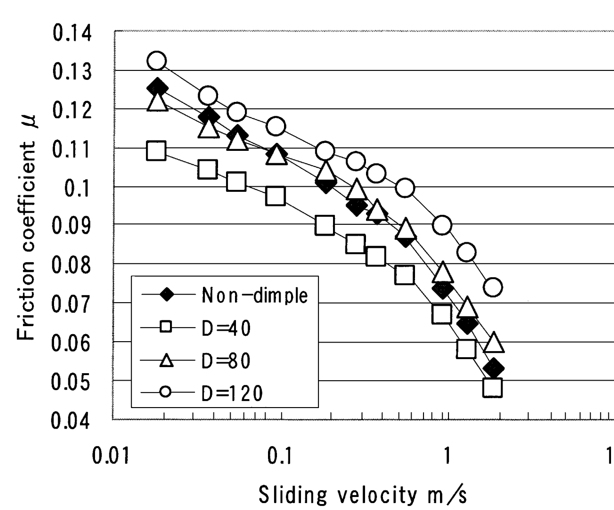

Fig. 7. Frictional properties of surfaces with 15% density dimples.

4. Discussion

From the results, it was confirmed that in dimples where the size was less than 80 μm and the density of around 15% can reduce friction. However, even for these dimples, no friction reduction was found at higher sliding velocity. When the size of dimple was 120 μm, friction coefficients were the same as the non-dimpled sample at the lower sliding velocity. However friction coefficients increased, as the sliding velocity became higher.

The differences observed in the effect of dimpling on the friction coefficient can be considered to be due to two competing effects of the dimples.

One positive effect of the dimples was to act as oil reservoirs. These oil reservoirs assist the formation of a lubricating film which is pulled in to the contact area due to viscous flow of the oil as shown Fig. 9. As a result, friction was reduced.

However, a negative effect of the dimples was to increase the contact pressure due to the decrease in the area of the contact surface. The contact areas for both non-dimpled and dimpled samples after friction test at 50 N are shown in Figs. 10 and 11. The white central part is the contact area. It can be seen that the width of the contact area does not change and, therefore, when the contact surface was dimpled, the load is supported by a smaller area such that contact pressure and friction were increased. Considering the effect of the dimpled density, there appears to be an optimum value for friction reduction. When the dimpled density was 7.5%, there was no big change in friction. However, when the dimpled density was 15%, the friction was reduced. It is thought that for this density, the positive effect of oil supply from the reservoirs is larger than the negative effect of decreased contact surface when dimpled density. However, when the dimpled density was 30%, the friction was increased. So it can be concluded there was a limit to the beneficial effect of lubricating oil being supplied to the contact area, and there was an optimum density distribution of the dimples. These competing effects are shown in Fig. 12.

The influence of the size of the dimples was also considered. When the size of dimple became large, the possibility that the dimples would be located at the edge of the contact area would increase, as shown in Fig. 13. In this situation it would be easy for the oil accumulated inside the dimples to leak out of the contact area. So the

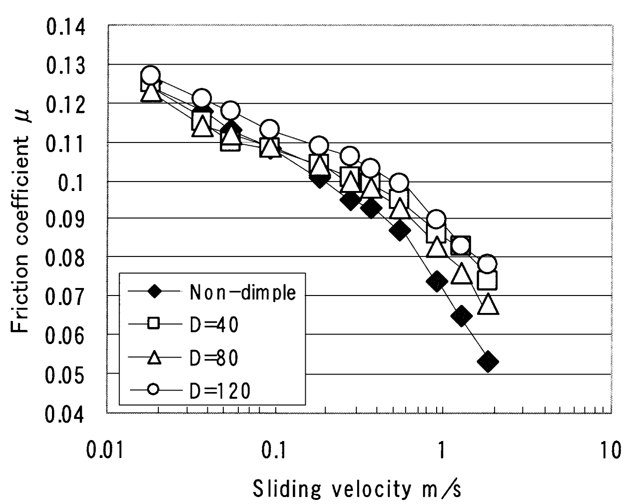

Fig. 8. Frictional properties of surfaces with 30% density dimples.

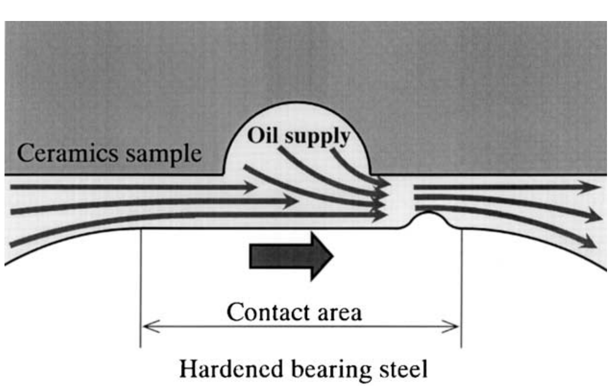

Fig. 9. Effect of dimple acts as oil reservoirs.

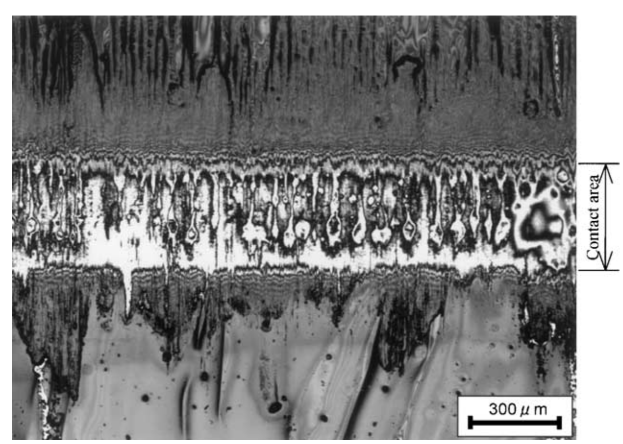

Fig. 10. Contact area of lapped surface with no dimple.

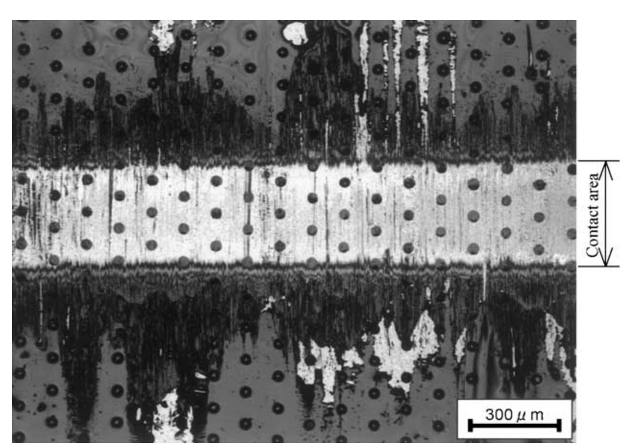

Fig. 11. Contact area of surface with dimple.

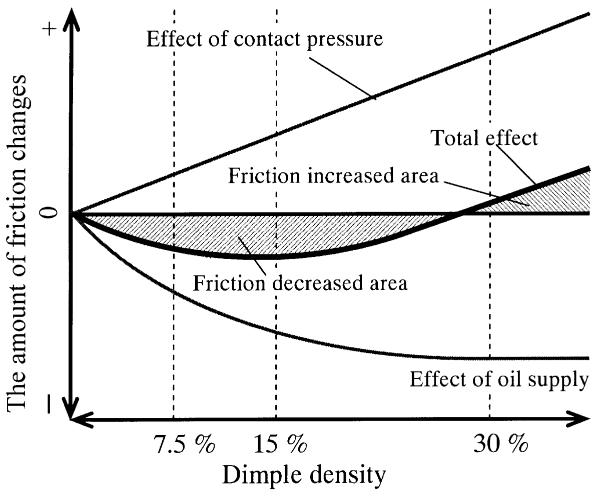

Fig. 12. Effect of dimple density.

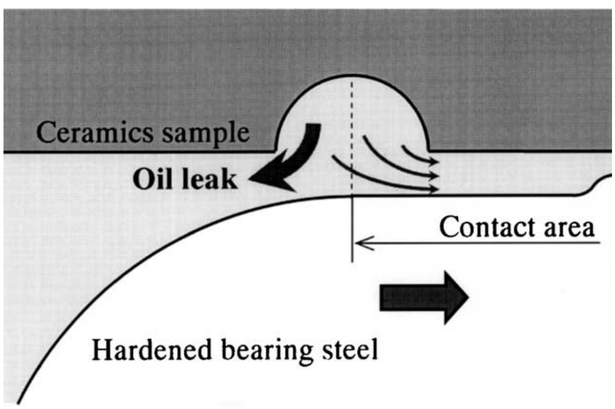

Fig. 13. Effect of dimple which located out of contact area.

lubricating oil supplied to the contact area was decreased, and the friction was increased.

The influence of sliding velocity was considered to be as follows. When the sliding velocity was low, the lubricating film, which existed in the contact area, became thin and the effect on the reduction of friction by the lubricating oil was large. However, when the sliding velocity was higher, the lubricating film became thick, and the lubricating effect was reduced. Under these conditions, the negative effect of the reduction in contact area caused by dimpling was the largest influence, and so the friction was increased.

From the above reasons, it was found that under these test conditions, the smallest sized dimples with a density distribution of 15% were most effective for friction reduction under mixed lubrication conditions.

5. Conclusions

Frictional properties of a micro-dimpled ceramic surface were assessed through block-on-ring tests modeling line contact conditions. The findings were concluded as follows.

1. Adding dimples to the sliding surface can lead to both positive and negative effects. These effects are dependent on the size and density of the dimples, and the frictional condition
2. Under the test conditions, dimples with a density distribution of about 15% and size of 40 μm were most effective for reducing friction.
3. Under conditions where the lubrication film is thin, the positive effect of the dimples acting as oil reservoirs exceeds the negative effect of increased contact pressure and friction is reduced. However under conditions where the lubrication film is thick, the opposite is observed, and no reduction in friction is observed.

Acknowledgements

This work has been supported by METI, Japan, as part of the Synergy Ceramics Project. Part of the work has been supported by NEDO. The authors are members of the Joint Research Consortium of Synergy Ceramics.

References

1. Kitamura, K., Takebayashi, H., Ikeda, M. and Percoulis, H.M., Development of ceramic cam roller follower for engine application, *SAE Tech. Paper*, 1997, 972774.
2. Kato, A. and Yasuda, Y. An analysis of friction reduction techniques for the direct-acting valve train system of a new-generation lightweight 3-liter V6 Nissan engine, *SAE Tech. Paper*, 1994, 940992.
3. Wong, H. C., Umehara, N. and Kato, K., The effect of surface roughness on friction of ceramics sliding in water. *Wear*, 2001, **218**, 237–243.
4. Blatter, A., Maillat, M., Pimenov, S. M., Shafeev, G. A., Simakin, A. V. and Loubnin, E. N., Lubricated sliding performance of laser-patterned sapphire. *Wear*, 1999, **232**, 226–230.
5. Ronen, A., Etsion, I. and Kligerman, Y., Friction reducing surface-texturing in reciprocating automotive components. *Tribol. Trans.*, 2001, **44**(3), 359–366.
6. Tejima, Y., Ishiyama, A. and Ura, A., The influence of pores at sliding faces and the pores diameter on mechincal seals performance (in Japanese). *J. Jpn. SOC Tribologis.*, 1999, **44**(6), 444–451.
7. Tejima, Y., Ishiyama, A. and Ura, A., The influence of rounded pores' diameter and depth at sliding faces for coefficient of friction under oil lubrication (in Japanese). *J. Jpn. SOC Tribologis.*, 1999, **44**(10), 816–823.
8. Wakuda, M., Yamauchi, Y. and Kanzaki, S., Effect of workpiece properties on machinability in abrasive jet machining of ceramic materials. *Precision Eng.*, 2002, **26**, 193–198.
9. Wakuda, M., Yamauchi, Y. and Kanzaki, S., Influence of micromachining on strength degradation of silicon nitride ceramic. *J. Manuf. Eng.*, 2002, **216**(B1), 55–60.