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Failure Analysis of a Ball in the Nuclear Fuel Exchanger

†H. P. Kim, D. J. Kim, S. S. Hwang, M. K. Joung,
Y. S. Lim, and J. S. Kim

Nuclear Material Technology and Development Division
Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Taejon, KOREA

Failure analysis of the latch ram ball and the C-ram ball with the trade name AFBMA Gr. 50 Colmonoy No. 6, has been performed to identify the root cause of the failure. The study required the extraction of the both failed and normal balls from the nuclear fuel exchanger. Microstructures of both balls were examined after polishing and etching. Breaking tests of both the ball revealed similarity in cleavage surfaces. Fracture surfaces of both failed ball and normal ball after breaking test were examined with SEM and EDX. Microstructure of the ball revealed an austenite phase with coarse Cr rich precipitate. Indented marks observed on the surface of the failed ball are believed to be produced by overloading. In the light of the afore mentioned observations and studies, the failure mechanism of the ball in nuclear fuel exchanger seem to be caused by impact or mechanical overloading on ball.

Keywords *: latch ram ball, C-Ram ball fuel exchanger, breaking test, transgranular cleavage, failure*

1. Introduction

Failure of the latch ram ball and the C-ram in fuel exchanger would manifest in enhancement of the maintenance cost and also prolong the fuel exchange period. The failure mechanism of the latch ram ball and the C-ram ball has not been published to the best of authors' knowledge and research. The failure mechanisms of ball used in industry are generally fatigue and wear.[1,2] Most (>90%) of the balls used in world market are made of SAE 52100 or its equivalent.[3] Typical chemical composition (wt. %) of SAE 52100 is 1.0 C, 0.25 Si, 0.35 Mn, 1.5 Cr, and the rest in iron. SAE 52100 is very tough material. Breaking force required for the ball having a diameter of 9.5 mm is about 150 KN. However, chemical composition of SAE 52100 is completely different from the latch ram ball and the C-ram ball used in fuel exchanger. In this work, failure mechanisms of the latch ram ball and the C-ram ball in fuel exchanger have been studied.

2. Experiment

The latch ram ball and the C-ram ball used in this study were AFBMA GR 50 Colmony No.6 and their diameters were 9.5 mm and 12.7 mm, respectively. The chemical composition (wt. %) of the latch ram ball was 2.87 B, 0.66 C, 0.09 Co, 13.02 Cr, 4.12 Fe, 4.38 Si, and the balance Fe. Fracture surface and microstructure of failed ball in fuel exchanger was examined with SEM and EDS. Microstructures ware observed after polishing with 0.3 μm Al_2O_3 and etching with phosphoric acid. Normal ball taken from a fuel exchanger was decontaminated in 2%HF, 20%HNO_3, 78% H_2O solution with an operations voltage of 6V at room temperature. Braking rest of the normal ball was performed and fracture surface and microstructure of the ball were also examined with SEM and EDS.

3. Results

3.1 Fracture surface observation of failed latch-ram ball and C-ram ball

Fracture surface of failed latch ram ball is shown in Fig. 1. Parts marked as A and B represent the broken edges of the fracture surface. V groove (marked as C in Fig. 1) was observed in upper right region on the fracture surface. Brittle fracture was also observed some part (mark D) of the fracture surface. However, most of the fracture surface show abraded and pressed appearance, which may be attributed to the rubbing of the cracked ball during rotation of the ball in its position.

Fracture surface of failed C-ram ball is shown in Fig.

†Corresponding author: hpkim@kaeri.re.kr

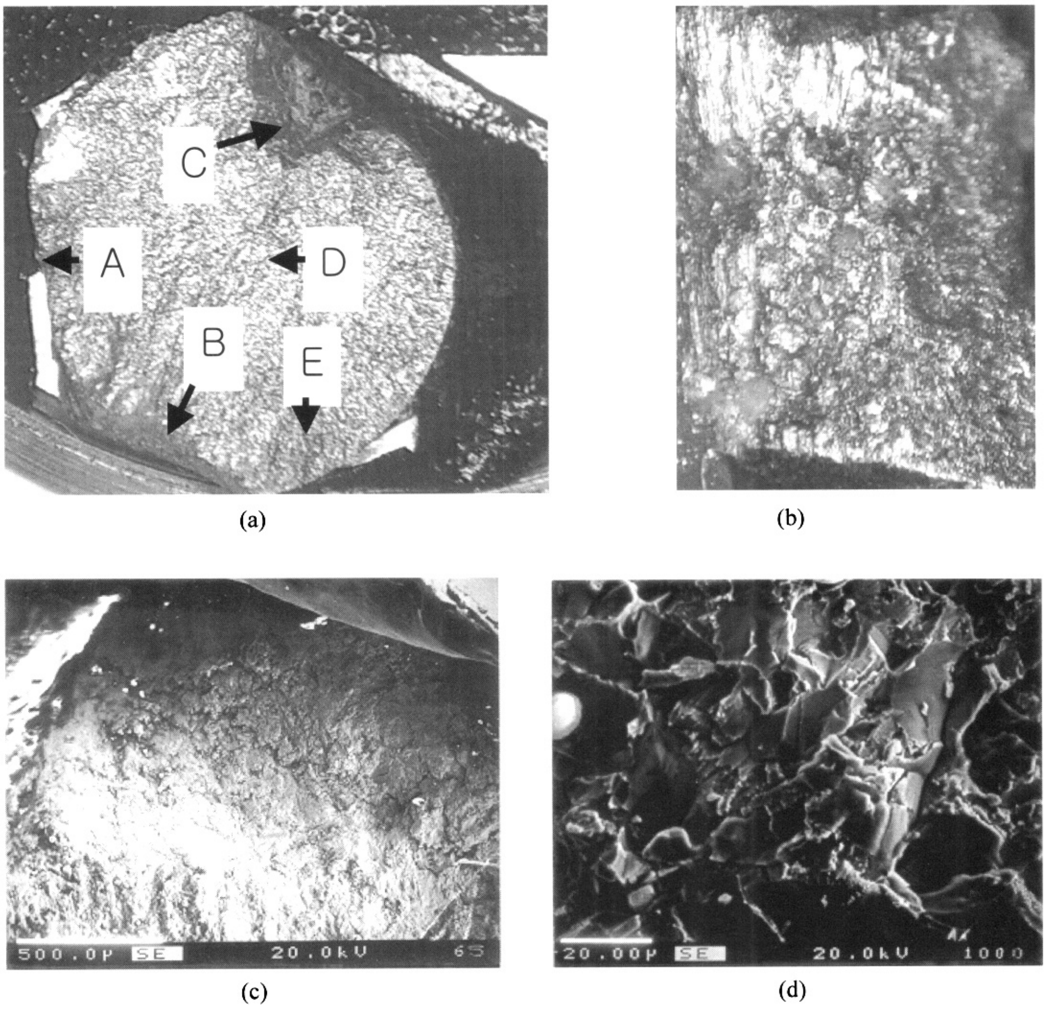


Fig. 1. Fracture surface of latch ram ball: (a) whole fracture surface; (b) magnification of V groove marked C in Fig. 1(a); (c) magnification of region marked D in Fig. 1(a);and (d) magnification of region marked E in Fig. 1(a).

2. Part marked as A and B represents the broken edges of the fracture surface (as in Fig. 1 for latch ram ball bearing). Some part of the fracture surface (e.g. part D in Fig. 2) show brittle fracture appearance. However, most of the fracture surface (e.g. part E in Fig. 2) shows abraded and pressed appearance, which may be attributed to the rubbing of the cracked ball bearing during rotation of the ball bearing in its position. The phenomenon of abraded and pressed appearance was more extensive in case of C-ram ball and the latch ram ball.

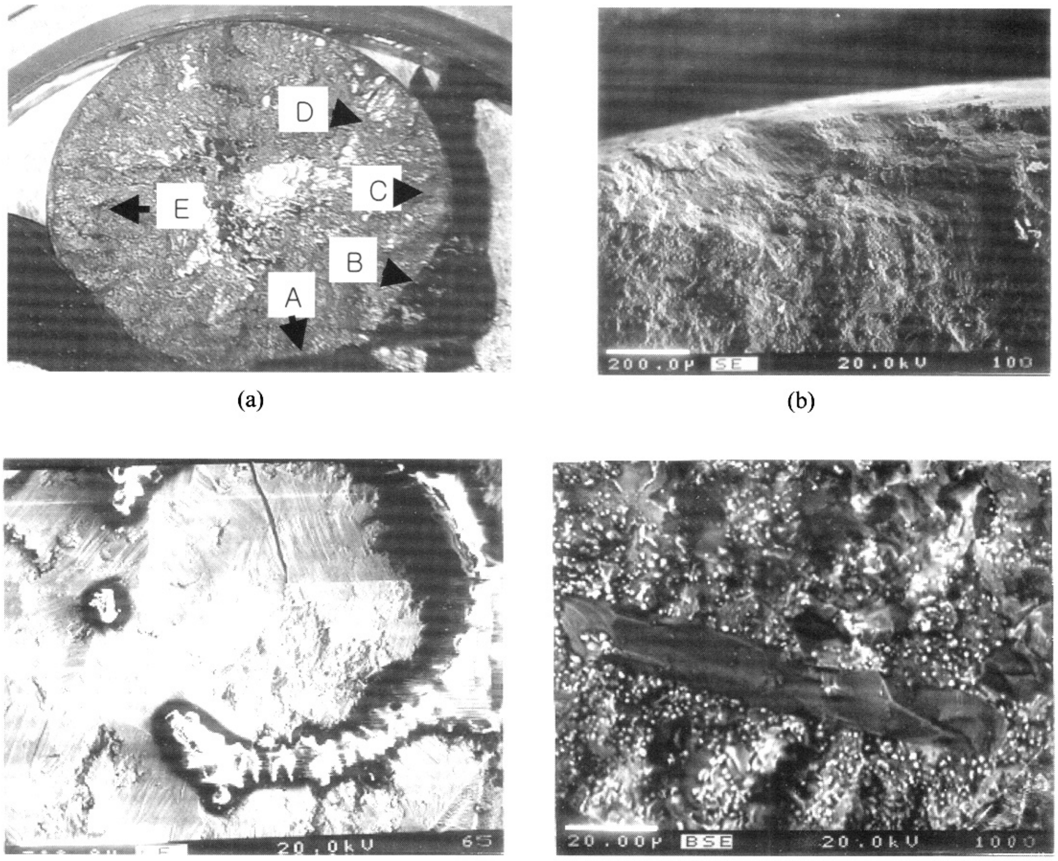
Some parts of the ball surface were indented by impact or mechanical overloading (Fig. 3). The indented marks can be discerned by naked eyes. Long acicular precipitate was found on the fracture surface of the ball (Fig. 2)

3.2 EDS analysis of failed latch-ram ball and C-ram ball

The precipitate morphology in latch ram ball and EMPA analysis of the precipitate is shown in Fig. 4. The acicular precipitate is Cr borocabide as can be seen from carbon and boron content of the precipitate. Shape and distribution of the precipitate showed that it was formed by dendritic growth. Carbide content on the polished surface was high. The precipitate morphology in C-ram ball and EMPA analysis of the precipitate are shown in Fig. 5. Shape and distribution of the precipitate were essentially the same for both latch ram ball and C-ram ball, as may be expected from similarity in chemical composition and heat treatment of the both balls.

3.3 Breaking force and fracture surface of a sound latch-ram ball after breaking test

Breaking and hardness tests of both the decontaminated latch ram balls and the normal one were performed to identify failure mechanism and find out the basic cause of failure such as fabrication defects and abnormal opera-



(a) (b) (c) (d)

Fig. 2. Fracture surface of C-ram ball: (a) whole fracture surface; (b) magnification of region marked C in Fig. 2(a); (c) magnification of region marked D in Fig. 2(a);and (d) magnification of region marked E in Fig. 2(a).

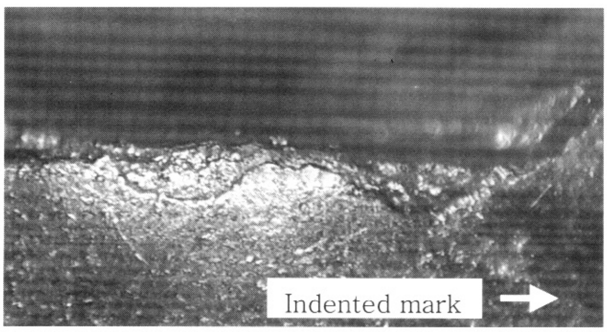


Fig. 3. Ball surface of C-ram ball with indented mark.

tion of the failed ball. Possible failure mechanisms of the failed ball could be mechanical overloading, fatigue, creep, stress corrosion cracking, corrosion fatigue and wear. The breaking force of the sound ball was about 25 KN. Hardness of the sound ball and failed ball were almost the same and about 58 HRc.

Fracture surface of a sound latch ram ball after breaking rest is shown in Fig. 6. It may be noted from the figure that the edge of the ball in contact with a loading fixture has been shattered and the contact location between two balls have also crushed. Circular edge of the ball that shattered during breaking test was in line contact with a loading fixture, while the location between the two balls was in point contact. Therefore, compressive force at a location between the two balls is higher than at location in line contact with a loading fixture. Consequently, it seems that cracks would be preferentially initiated at a point contact location between the two balls because of higher compressive force. Fracture surface of the sound latch ram ball after breaking test could be classified into two regions according to appearance of fracture surface ;(i) region near the point contact between the two balls where cleavage fractures initiated and propagated on many parallel planes, trans-passing through grain boundaries (Fig. 7(a)) and (ii) region covering most fracture surface except a small region around point contact where cleavage fracture occurred along specific planes which are limited within grain (Fig. 7(b))

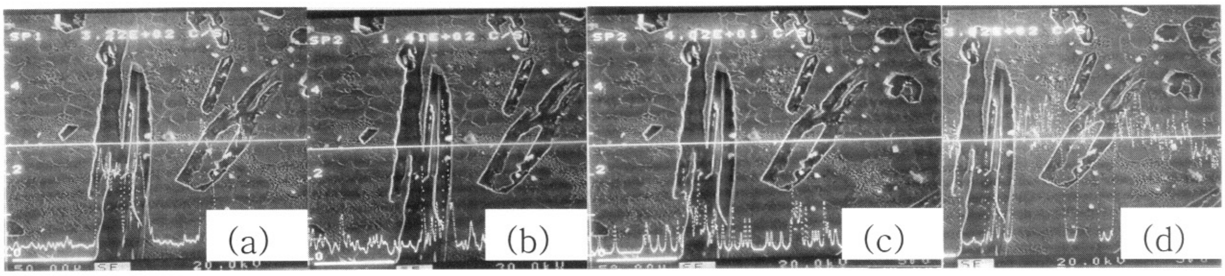


Fig. 4. EDS analysis of precipitate in latch ram ball bearing: (a) Cr; (b) B; (c) C; and (d) Ni.

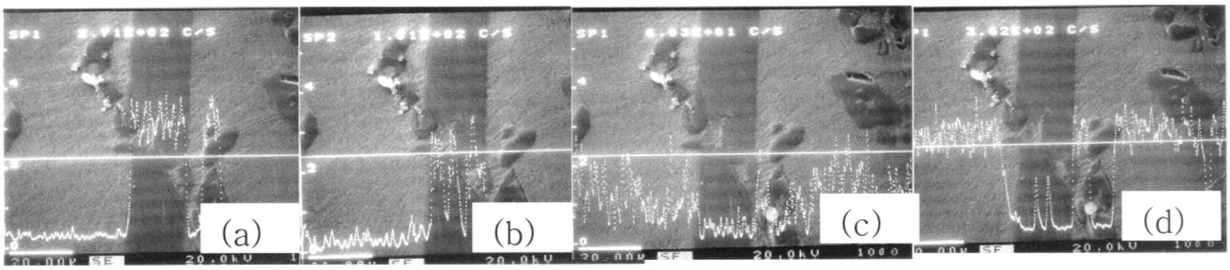


Fig. 5. EDS analysis of precipitate in C-ram ball bearing: (a) Cr; (b) C; (c) Fe; and (d) Ni.

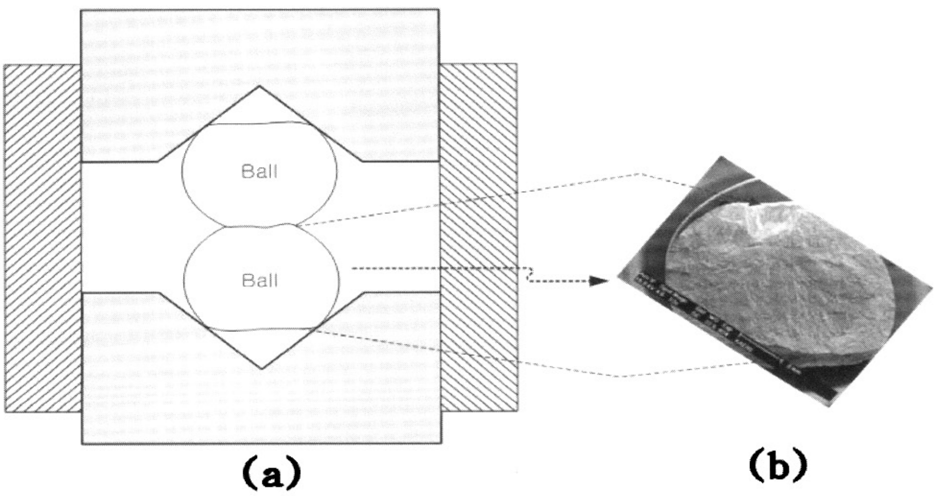


Fig. 6. (a) Schematic of ball shape after breaking test. (b) fracture surface after breaking test.

3.4 EDS analysis of a fracture surface of sound latch ram ball

EDS analysis of acicular precipitate and matrix of a fracture surface of latch ram ball is shown in Fig. 8. Acicular precipitate consists of Cr borocarbide as in case of the failed latch ram ball. Major alloying elements in all the areas measured by EDS have almost the same chemical composition as measured by ICP method.

4. Discussion

Possible failure mechanisms of the latch ram and C-ram ball could be mechanical fracture by overloading, fatigue, creep, wear, stress corrosion cracking, corrosion fatigue and hydrogen embrittlement. The environment of the ball was reviewed thoroughly to have an insight into the failure mechanism of the ball. The ball was exposed to hot water and subjected to stress during fuel exchange. Temperature of the hot water was less than 100℃, however, the stress acting on the ball in a fuel exchanger was not available. The fuel exchanger was usually controlled by computer in normal operation and the force acting on the ball was less than the preset value. However, the fuel exchanger was sometimes controlled manually in abnormal circum-

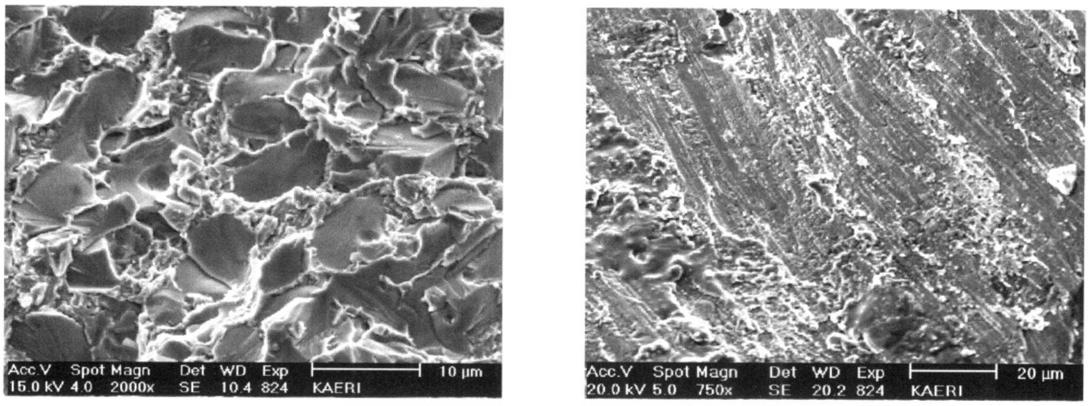
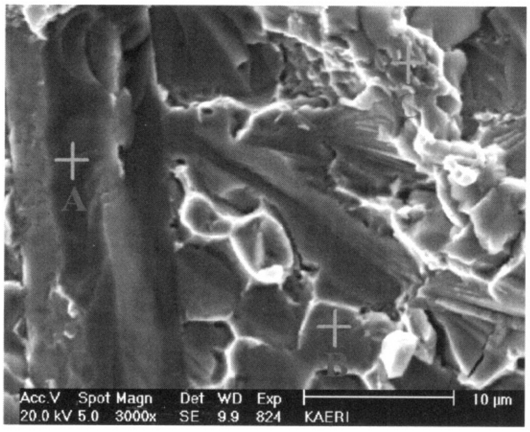


Fig. 7. Magnification of fracture surface: (a) A region of Fig. 6(b); and (b) B region of Fig. 6(b).



Element	Ni	Cr	Fe	Si
Spot A	14.23	82.20	3.57	
Spot B	90.02	6.58	2.50	
Spot C	88.15	6.64	3.43	1.78

Fig. 8. EDS analysis of precipitate (marked A) and matrix (marked B and C) on fracture surface of sound ball after breaking test.

stances. That is, when the fuel exchanger could not insert fuel assembly into pressure tube nor pull fuel assembly out from it, operation of the fuel exchanger was switched from automatic mode to manual mode and the ball bearings in the fuel assembly were subject to higher force or higher impact.

Creep may be ruled out from failure mechanism due to low temperature of the ball resulting for exposure to the environment. Fatigue and corrosion fatigue may also be excluded from failure mechanism because there is no evidence of striation marks, which typically appear on fracture surface during fatigue failure.[4] Wear may be ruled out on the basis that ball surface did not show any trace of wear even though indented marks were observed at several location of the ball surface. Damage by wear usually shows abrasive wear or adhesive wear appearance. Breaking strength of 3/8 inches diameter ball of AFBMA Gr. 50 Colmonoy No. 6 is about 26 N, while that of SAE 52100 is about 150 N, implying that AFBMA Gr. 50 Colmonoy No. 6 is very brittle material.

The fracture surfaces of the failed ball (as shown in Fig. 1(b), Fig. 1(c), Fig. 2(b), and Fig. 2(c) appears to be located on well defined, low energy crystallographic plane, and may be termed as brittle fracture surface. The brittle fracture surface may be produced by transgranular stress corrosion cracking or mechanical overloading of brittle material. However, comparison of fracture surface of failed ball and sound ball after breaking test has revealed a number of similarities. For example, fracture surface of failed ball as shows in Fig. 1(b), Fig. 1(c), Fig. 2(b), and Fig. 2(c) are similar to the corresponding surface of sound ball as shows in Fig 7. Similarly, Area C (Fig 1(a), Fig 2(a)) and high magnification of the Area C of fracture surface of failed ball (Fig. 1(b)) correspond well to Area X (Fig. 6(b) and higher magnification of the Area X (Fig. 7(a)) of fracture surface of sound ball, respectively. The similarity was also observed between Area D (Fig. 1(a), Fig. 2(a) and higher magnification of the Area D (Fig. 3(b)) of fracture surface of failed ball and the corresponding Area Y (Fig. 6(b) and higher magnification of the Area Y (Fig. 7(b)) of fracture surface of sound ball, respectively. A region near the point contact between the two balls shows that cleavage fractures initiated and propagated on many parallel planes. Other region covering most fracture surface with the exception of a small region around point contact shows that crack propagates, along specific plane in each grain. In addition, indented marks were observed at several locations of the fractured ball surface. Breaking force of the 9.5 mm diameter ball in fuel exchanger was 1/6 of the normal SAE 52100 ball. The ball in fuel exchanger was very brittle because it has many coarse precipitate in the matrix.

The reason for using brittle material as constituent of ball seems to prevent the fuel exchanger from deformation by breaking the ball preferentially in case of mechanical overloading.

The fore mentioned similarity in fracture surface of failed ball and that of sound ball after breaking test, brittleness of the ball and presence of indented marks on surface of the failed ball suggest that failure mechanism of the failed all is mechanical overloading or impact, leading to brittle cleavage near initiation point and then transition to brittle fracture along certain crystallographic plane in each grain.

5. Conclusions

Microstructure of the ball was an austenite phase with coarse Cr rich precipitate. Fracture surface of failed ball showed abraded appearance and brittle transgranular cleavage. The abraded appearance on the fracture surface seemed to be produced by repeated stress acting on cracked ball surface. The brittle transgranular cleavage on the fracture surface was composed to two regions; (1) region near crack initiation where cleavage fractures initiated and propagated in many parallel planes; (2) region covering most fracture surface except a small region around point contact where cleavage propagated along specific planes in each grain. Indented marks on failed ball surface were observed, suggesting that the ball bearing was subject to mechanical impact or overloading. Fracture surface of sound ball examined following breaking test shows only brittle transgranular cleavage like fracture surface of failed ball. Breaking force of 50 Colmony No. 6 is about 26 N while that of SAE 52100, which is usually used in ball making, is about 150 N, it implies that AFBMA Gr. 50 Colmonoy No. 6 is very brittle material. Therefore, failure of the ball bearing in nuclear fuel exchanger seems to be caused by impact or mechanical overloading on ball, leading to brittle transgranular cleavage.

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