Available online at www.sciencedirect.com
SCIENCE DIRECT®
Wear 259 (2005) 958–963
WEAR
www.elsevier.com/locate/wear

Case study

Wear of cast metal–metal pairs for total replacement hip prostheses

M.A.L. Hernández-Rodríguez [a,*], R.D. Mercado-Solís [b], A.J. Pérez-Unzueta [b], D.I. Martinez-Delgado [b], M. Cantú-Sifuentes [a]

[a] *Corporación Mexicana de Investigación en Materiales S.A de C.V, Boulevard Oceania 190, Fraccionamiento Saltillo 400, Saltillo, Coahuila, México, C.P. 25290, Mexico*
[b] *Facultad de Ingeniería Mecánica y Eléctrica, Universidad Autonoma de Nuevo Leon, Mexico*

Received 2 September 2004; received in revised form 20 January 2005; accepted 10 February 2005
Available online 10 May 2005

Abstract

The first metal–metal prostheses were implanted during the 1960s decade. Many of these implants showed unsatisfactory short-term results due to poor designs and inappropriate manufacturing methods leading to high friction and wear. However, in the cases where the implants lasted for 20 years or longer, it was found that they exhibited a highly polished surface finish, very small changes in dimensions and low wear rates. These findings brought a revival for the metal–metal implants, which at that time, were being progressively taken over by the metal–polymer, metal–ceramic and ceramic–ceramic pair materials.

The present work evaluates the influence of dimensional and microstructural parameters upon the wear behaviour of metal–metal hip implants of a Co–Cr cast alloy by means of laboratory simulation. A total of 10 pairs (acetabular cup and femoral hemisphere) were manufactured with varying diametral clearances, carbon content (0.21 and 0.31 wt.%), and microstructures (as-cast, partial and complete carbide solutions) achieved by heat treatment. The pair specimens were subsequently tested in a newly developed hip simulator under severe reciprocating sliding conditions at a frequency of 1.5 Hz, a constant load of 2 kN and bovine serum solution as lubricant. It was found that pair specimens with large diametral clearances exhibited higher amounts of wear compared to those samples with smaller diametral clearances. In terms of microstructural parameters and carbon content, pair specimens with the as-cast and partial solution microstructures (with carbide volume fractions of about 10%) exhibited less amounts of wear than those with complete carbide solution microstructures (with carbide volume fractions of about 5%). This implies that a higher content of carbon enhances wear resistance only if the carbon is precipitated as carbides and not as solution within the matrix.

Keywords: Metal–metal hip implants; Hip simulator; Co–Cr cast alloys; Wear

1. Introduction

The total hip arthroplastic surgery was a major medical advance of the 20th century. There are two main types of hip prosthesis: total and partial. In the partial prosthesis the contact is made between the pelvis bone and the femoral implant, whereas in the total prosthesis the contact is made between the two elements of the artificial implant: the acetabular cup and the femoral head. The materials used in this medical application must possess satisfactory mechanical properties such as toughness and fatigue strength, wear and corrosion resistance, and must not pose a risk to human body's health (biocompatibility).

Most of the first metal–metal (McKee-Farrar) total hip prostheses implanted during the 1960s decade showed unsatisfactory short-term performance mainly due geometrical inaccuracies which led to high frictional forces and increased wear [1,2,3,4,5]. Nevertheless, in some cases the implants lasted for two decades or more without osteolysis [2,5,6,7] and negligible wear [2,8,9,10,11]. In recent years, the use of second generation Co–Cr alloy metal–metal bearing joints in total hip arthroplastic surgery represents an attractive alter-

* Corresponding author. Tel.: +52 844 4113200; fax: +52 844 4113200.
E-mail address: malhdz@comimsa.com.mx (M.A.L. Hernández-Rodríguez).

0043-1648/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2005.02.080

Table 1
Chemical composition (wt.%) of the pair specimens used in this investigation

	C	S	Mn	Si	P	Cr	Ni	Mo	Nb	W	Fe	Co
ASTM F75/98 standard	0.35 max.	0.004 max.	1.00 max.	1.00 max.	0.005 max.	27.00–30.00	1.00 max.	5.00–7.00	–	0.04 max.	0.75 max.	Bal
Femoral hemispheres	0.21	0.001	0.34	0.65	0.004	27.6	0.21	6.36	0.02	–	0.75	Bal
	0.31	0.001	0.39	0.7	0.004	27.9	0.24	6.51	0.02	–	0.70	Bal
Acetabular cups	0.31	0.001	0.39	0.7	0.004	27.9	0.24	6.51	0.02	–	0.70	Bal

native to the traditional metal–polyethylene pairs [12]. In Europe alone 60,000 total replacement hip implants have been reported with satisfactory results due to their low wear [13].

Recent investigations revealed that wear of metal–metal (Co–Cr alloys) joint bearings manufactured by different processes (wrought, forging and cast) is strongly influenced by the gap (clearance) between the acetabular cup and the femoral head [14,15,16,17]. However, in the implants produced by casting, there is still lack of information about the effect of carbon content and carbide volume fraction upon the wear performance of the bearing surfaces. The propose of this study is to evaluate the influence of carbon content and microstructural factors upon the wear behaviour of two Co–Cr alloys by means of laboratory simulation under severe loading conditions.

2. Materials and methods

A total of 10 prototype specimen pairs (acetabular cups and femoral hemispheres) were manufactured by the investment casting method. All the acetabular cups have the same chemical composition whereas the femoral hemispheres were produced with two different carbon contents: 0.21 and 0.31 wt.%. All the test specimens comply with the chemical composition of the ASTM F75/98 [18] standard specification for cobalt-28 chromium-6 molybdenum casting alloy for surgical implants (Table 1).

Three different femoral hemisphere microstructures were studied: (1) as-cast condition, (2) complete carbide solution and (3) partial carbide solution. All the acetabular cup specimens were in the as-cast condition. To produce the complete carbide solution, the femoral head specimens were heated to a temperature of 1220 °C during 4 h, followed by water quenching. The partial carbide solution was achieved by a two-stage heat treatment: (a) heating to 1220 °C at a heating rate of 100 °C/min with a holding time of 15 min, followed by water quenching; (b) annealing by heating to 815 °C during 10 h. Micrographs of the three different microstructures are shown in Figs. 1–3 for the as-cast, complete solution and partial solution conditions, respectively. The as-cast microstructure (Fig. 1) shows blocky-shape $M_{23}C_6$ primary carbides (average size 10–30 μm). On the other hand, the complete solution microstructure (Fig. 2) exhibits relatively smaller globular carbides (average size 2–10 μm), which resulted from the transformation of the as-cast $M_{23}C_6$ primary carbides into M_6C carbides where M is Cr, Mo and Co. The partial solution microstructure (Fig. 3) exhibits similar carbide sizes but different morphologies compared to those observed in the as-cast microstructure. After heat treatment, all the samples were finely turned, ground and polished using the superfinishing technique. A stylus profile meter was used to measure the average surface roughness (R_a) of the acetabular cup and femoral head test specimens. Finally, the diametral clearances of the pairs were determined using a coordinate measuring machine. The values of R_a, diametral clearances and volume fraction of carbides are shown in Table 2 for each femoral head. A schematic drawing of the contact between the femoral head and acetabular cup is shown in Fig. 4.

Wear testing was performed in a newly developed hip joint simulator (Fig. 4a) especially designed to mate the prototype

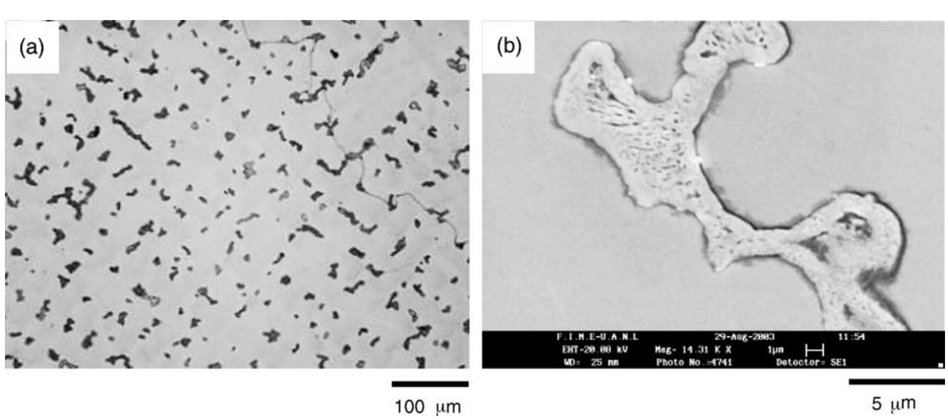

Fig. 1. Optical (a) and high magnification SEM (b) micrographs of the typical as-cast femoral head microstructure.

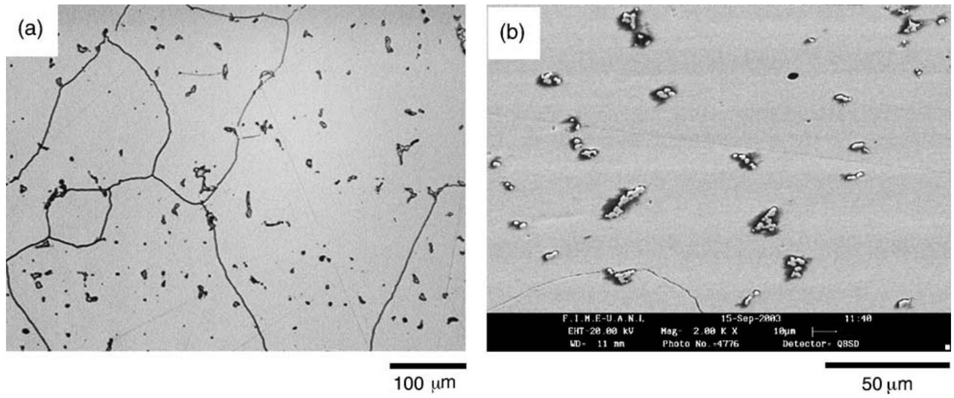

Fig. 2. Optical (a) and high magnification SEM (b) micrographs of the complete carbide solution femoral head microstructure.

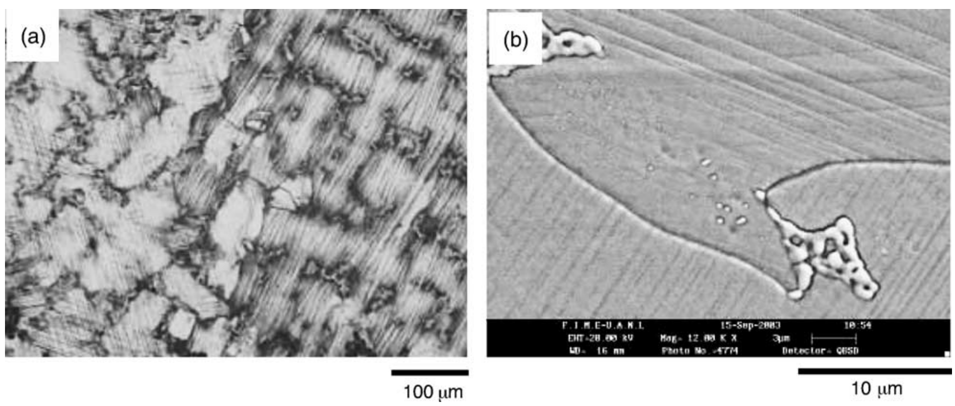

Fig. 3. Optical (a) and high magnification SEM (b) micrographs of the partial carbide solution femoral head microstructure.

hip implant specimens as shown schematically in Fig. 4b. This laboratory facility is capable of producing unidirectional reciprocating sliding to simulate the flexo-extension at an angle of ±23° under a constant vertical load.

In this study, a frequency of 1.5 Hz and constant load of 2 kN were selected since these conditions represent the worst case scenario involved during a normal walking cycle. Bovine serum solution (30% in distilled water) was used as a lubricant, in combination with antibacterial and antifungal agents to avoid biological contamination. The simulations were run at an average ambient temperature of 34 °C, similar to human body. The tests were stopped every 100 thousand cycles to weight the femoral head specimen using an analytical balance (accuracy of 0.1 mg) and to renew the lubricant. Before being weighted, the specimens were brushed with a soft nylon and washed with detergent. Finally, the specimens were ultrasonically cleaned to remove any dirt or debris adhered to its surface that could influence the weight measurement. All the pairs were tested to a total of 500 thousand cycles. The surface condition of the acetabular head specimens was examined after 100, 300 and 500 thousand test cycles using a scanning electron microscope (SEM) in the secondary elec-

Table 2
Values of average surface roughness (R_a), diametral clearance and carbide volume fraction of the femoral head test samples under investigation

Carbon content (wt.%)	Sample Id. (condition)	Average surface roughness, R_a (μm)	Diametral clearance (μm)	Carbide volume fraction (%)
0.21	4.1 (as-cast)	0.016	23	9.05
	4.2 (as-cast)	0.014	470	9.05
	5.1 (complete solution)	0.014	505	4.92
	5.2 (complete solution)	0.011	10	4.92
	5.5 (partial solution)	0.021	20	8.07
0.31	9.4 (as-cast)	0.013	5	12.61
	9.5 (as-cast)	0.013	132	12.61
	6.1 (complete solution)	0.017	−24[a]	5.77
	6.2 (complete solution)	0.010	5	5.77
	9.2 (partial solution)	0.017	72	10.6

[a] A negative clearance indicates that the femoral hemisphere is larger than the acetabular cup.

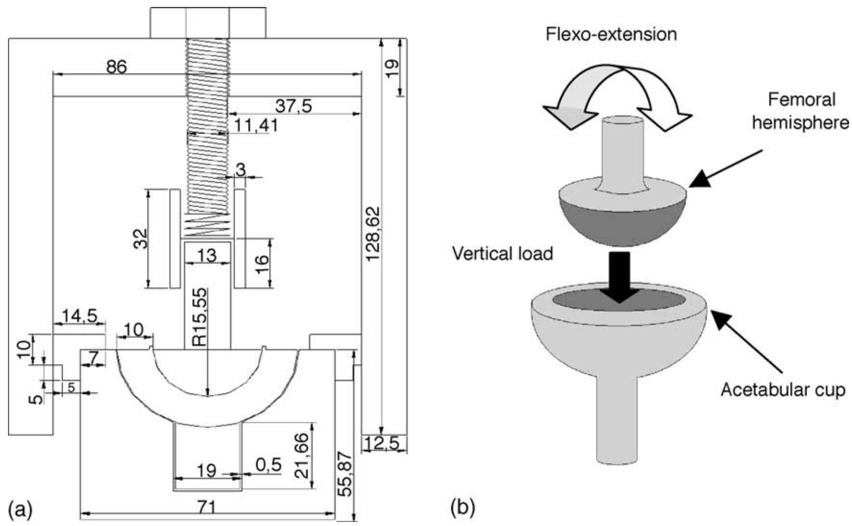

Fig. 4. (a) Drawing of the contact configuration of the hip joint simulator (dimensions in mm). (b) Illustration of the acetabular cup and femoral hemisphere pair contact (not to scale).

tron mode as well as qualitative elemental analysis using an energy dispersive spectrometer (EDS).

3. Results and discussion

Fig. 5 shows the progressive mass loss of the pair test specimens (cup and hemisphere) against number of test cycles throughout the simulation experiments, showing an almost linear relationship in all cases. It can be observed from the curves presented in Fig. 5 that the sample Id. 5.1 experienced more wear whereas sample Id. 9.5 exhibited less amounts of wear (168 and 35 mg, respectively) amongst all the test pair specimens. In addition, samples with large diametral clearances (see Table 2 and Fig. 5) showed higher values of wear than samples with small diametral clearances. The relationship between carbide volume fraction of the femoral hemisphere specimens and total wear (cup and hemisphere) throughout the simulation tests is presented in Fig. 6. The trend observed in this figure shows that the amount of wear is inversely proportional to the carbide volume fraction present in the microstructure of the femoral hemisphere samples. A regression analysis was performed with data of carbide volume fraction and diametral clearances (see Table 2), resulting in $p = 0.001$ and $r^2 = 0.92$.

Table 2 shows that after heat treatment of the femoral samples, there is not a direct relationship between the carbon content and the amount of surface carbides present in the microstructure. This is because the solution heat treatments tend to lower the carbide volume fraction in cobalt-base alloys. It is therefore important to point out that alloys with relatively high carbon content which were given the solution heat treatment, will not necessarily have high carbide volume

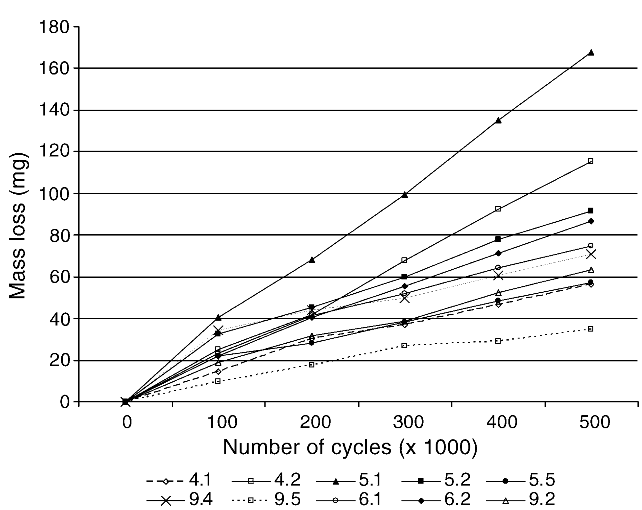

Fig. 5. Curves of mass loss vs. number of test cycles for the test pair specimens.

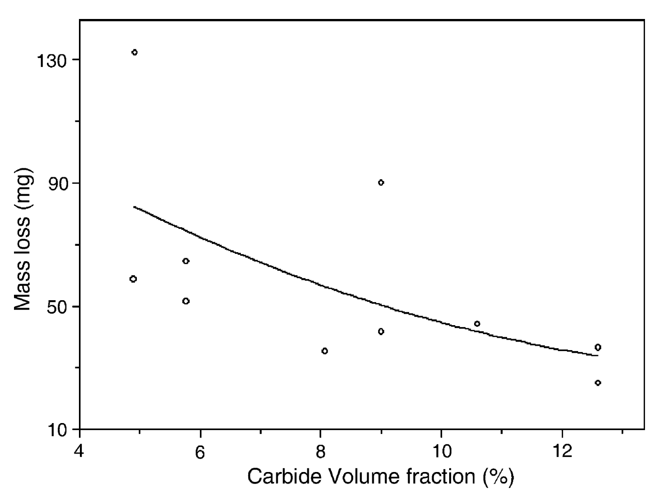

Fig. 6. Graph showing the relationship between carbide volume fraction in the femoral hemisphere specimens and total wear of the test pair specimens (cup and hemisphere) between 100,000 and 500,000 cycles.

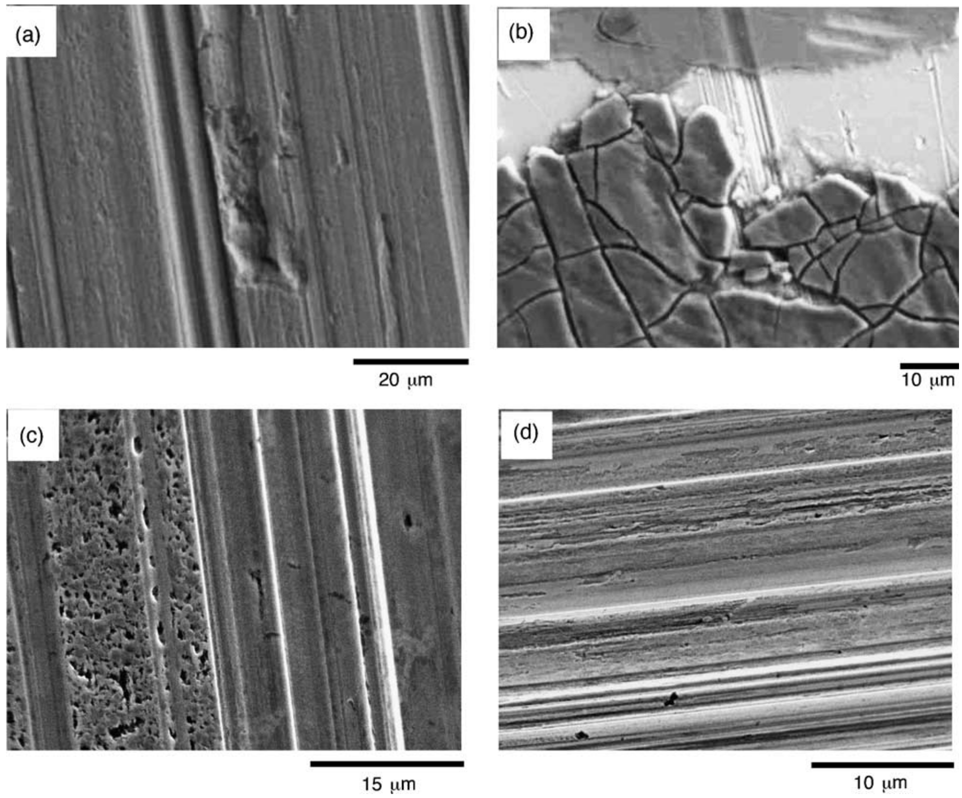

Fig. 7. SEM micrographs of femoral heads worn surfaces, (a) sample Id. 4.1, 100 thousand cycles showing abrasive wear groves, (b) sample Id. 5.2, 300 thousand cycles showing breakdowns of adhered lubricant film, (c) sample Id. 5.4, 500 thousand cycles showing surface micro pitts and (d) sample Id. 5.4, 500 thousand showing surface delaminations.

fractions because carbon is likely be dissolved within the matrix and not present as carbide precipitates. An example of this is samples Id. 6.1 and 6.2 which have relatively high carbon content but low carbide volume as opposed as samples Id. 4.1 and 4.2, which exhibit low carbon but relatively high volumes of carbides.

Scanning electron micrographs depicting the changes in surface condition of the femoral hemisphere specimens at different stages of the simulation tests are presented in Fig. 7. After 100 thousand cycles (Fig. 7a), common features observed in the femoral specimens were abrasive wear grooves typically 2–6 μm wide. Areas containing traces of lubricant films still adhered to the surface were also observed. The EDS analysis of these zones revealed high concentrations of carbon and oxygen along with other elements such as calcium, potassium and sodium, which are comparable to in vivo prostheses [19]. In some cases, particles of the lubricant film were found entrapped within the wear grooves. In addition, evidence was found of surface carbide detachments, thus enhancing surface abrasion as the dominant wear mechanism during the initial period of the tests. After 300 thousand cycles, a thicker and more adherent lubricant film was observed in many areas within the femoral samples. It was apparent that the film effectively separates the two contacting surfaces although in some areas the breakdown of this film was evident (Fig. 7b) arising in localised metal–metal contact. Micro pittings were observed in certain zones of the specimen surfaces. After 500 thousand cycles, a more severe pitted surface was observed in all the femoral hemisphere samples. Micro pits and surface delaminations were commonly observed as shown in Fig. 7c and d, respectively.

4. Conclusions

Wear tests were performed using a simulator that houses prototype samples of acetabular cups and femoral heads under severe loading conditions. The test pair specimens were manufactured from two Co–Cr alloys with different carbon contents and microstructures obtained by means of heat treatment. The experimental results showed that the wear of cast metal–metal implants is strongly influenced by the carbide volume fraction rather than carbon content. Dimensional accuracy (amount of clearance) was confirmed as a dominant factor in the wear performance of this type of implants. The hip joint simulator provided an effective way of accelerated wear testing and, thus, it can be regarded as a useful method to assist in further understanding the wear of bearing joint materials.

Acknowledgements

The authors would like to acknowledge CONACYT-Mexico, COMIMSA and APM for their support to this research. The technical assistance of G. Partida from the tribology lab is greatly acknowledged.

References

[1] S.C. Scholes, S.M. Green, A. Unsworth, The wear of metal-on-metal total hip prostheses measured in a hip simulator, Proc. Instn. Mech. Engrs. 215 Part H (2001) 523–530.
[2] H.C. Amstutz, P. Grigoris, Metal on metal bearing in hip arthroplasty, Clin. Orthop. 329 (Suppl.) (1996) 11–34.
[3] G.K. McKee, Total hip replacement- past, present and future, Biomaterials 3 (1982) 130–135.
[4] P.S. Walker, B.L. Gold, The tribology (friction, lubrication and wear) of all metal artificial hip joints, Wear 17 (1971) 285–299.
[5] S.A. Jacobsson, K. Djerf, O. Wahlstrom, 20 years result of McKee-Farrar vs. Charnley prosthesis, Clin. Orthop. 329 (Suppl.) (1996) 60–68.
[6] B.G. Weber, Experience with metasul total hip bearing system, Clin. Orthop. 329 (Suppl.) (1996) 69–77.
[7] B.O. Weightman, I.L. Paul, R.M. Rose, S.R. Simon, E. Radin, A comparative study of total hip replacement prostheses, J. Biomech. 6 (1973) 299–311.
[8] R.W. McCalden, D.W. Howie, L. Ward, Observation of the long term behaviour of retrieved McKee-Farrar total hip replacements implants, Trans. Orthop. Res. Soc. 20 (1995) 242.
[9] H. McKellop, P. Campbell, S.H. Park, Wear of retrieved metal-metal implants after two decades of clinical use, Trans. Comb. Orthop. Res. Soc. 2 (1995) 228.
[10] H. McKellop, S.H. Park, R. Chiesa, In vivo wear of three types of metal on metal hip prostheses during two decades of use, Clin. Orthop. 329 (Suppl.) (1996) 128–140.
[11] M. Schmidth, H. Weber, R. Schon, Cobalt Chromium molybdenum metal combinations for modular hip prostheses, Clin. Orthop. Rel. Res. 329 (Suppl.) (1996) 35–47.
[12] K. Brummitt, C.S. Hardaker, Estimation of wear in total hip replacement using a ten station hip simulator, Proc. Inst. Mech. Eng. J. Eng. Med. 210 (1996) 187–190.
[13] H. Wagner, M. Wagner, German clinical results with metasul bearings, in: C. Reiker, M. Windler (Eds.), Metasul: A Metal on Metal Bearing, Hans Huber, Bern, 1999, pp. 171–178.
[14] C.M. McNie, D. Dowson, The effect of radial clearance on lubrication in a metal on metal joint tested in a hip simulator, in: D. Dowson, C.M. Taylor, T.H.C. Childs, G. Dalmaz, Y. Berhier, L. Flamand, J.M. Georges, A.A. Lubrecht (Eds.), Thinning Films and Tribological Interfaces, Tribology Series 36, Elsevier, 2000, pp. 341–345.
[15] D. Dowson, C.M. McNie, A.A.J. Goldsmith, Direct experimental evidence of lubrication in metal-on-metal total hip replacement tested in a joint simulator, Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci. 214 (2000) 75–86.
[16] J.B. Medley, J.D. Bobyn, J.J. Krygier, F.W. Chan, M. Tanze, G.E. Roter, Elastohydrodynamic lubrication and wear of metal-on-metal hip implants, in: C. Rieker, S. Oberholzer, U. Wyss (Eds.), World Tribology Forum in Arthroplasty, Hans Huber, Bern, 2001, pp. 3–14.
[17] I.J. Udofia, Z.M. Jin, Elastohydrodynamic lubrication analysis of metal-on-metal hip resurfacing prostheses, J. Biomech. 36 (2003) 537–544.
[18] F75-98 Standard Specification for Cobalt-28 Chromium-6 Molybdenum Casting Alloy and Cast Products for Surgical Implants (UNS R30075). ASTM Book of standards, vol. 13.01, September 2001.
[19] M.A. Wimmer, C. Sprecher, R. Hauert, G. Tager, A. Fischer, Tribochemical reaction on metal-on-metal hip joint bearings: a comparison between in-vitro and in-vivo results, Wear 255 (2003) 1007–1024.