Optimization of Frictional Heating Parameters of Artificial Joint Materials by Taguchi Approach

Binnur SAGBAS[1] and M.Numan DURAKBASA[2]

[1] *Yildiz Technical University, Department of Mechanical Engineering,*
34349 Besiktas, İstanbul, Türkiye
+90 216 383 28 06
bsagbas@gmail.com

[2] *Vienna University of Technology,*
Department of Interchangeable Manufacturing and Industrial Metrology,
Karlsplatz 13/3113 A-1040 Wien, Austria
aum@mail.ift.tuwien.ac.at

Abstract- Previous measurements of frictional temperature rise on the surfaces of artificial joints have shown that temperature values could reach high levels that make hazardous effects on surrounding tissue and lubricant around the artificial joint. For reduction of this thermal damage, testing parameters and their effects were investigated by using Taguchi method and analysis of variance. Vitamin E blended ultra high molecular weight polyethylene (VE-UHMWPE) was used for acetabular inserts. These inserts were paired with CoCrMo femoral heads. In vitro frictional heating measurements were carried out on a custom made hip joint friction experimental set-up. 0.3 mm and 0.5 mm in diameter surface dimples were machined on the inner surface of acetabular cup samples. Different static loading, representing different body weights, applied with different walking duration. Bovine calf serum was used as lubricant and different amount of bone cement (PMMA) was added in the lubricant as third body abrasive particles. Temperature rises were recorded with embedded thermocouples. The experimental results demonstrated that the surface dimples were the major parameter on frictional heating, followed by applied load, amount of third body particles and time.

I. Introduction

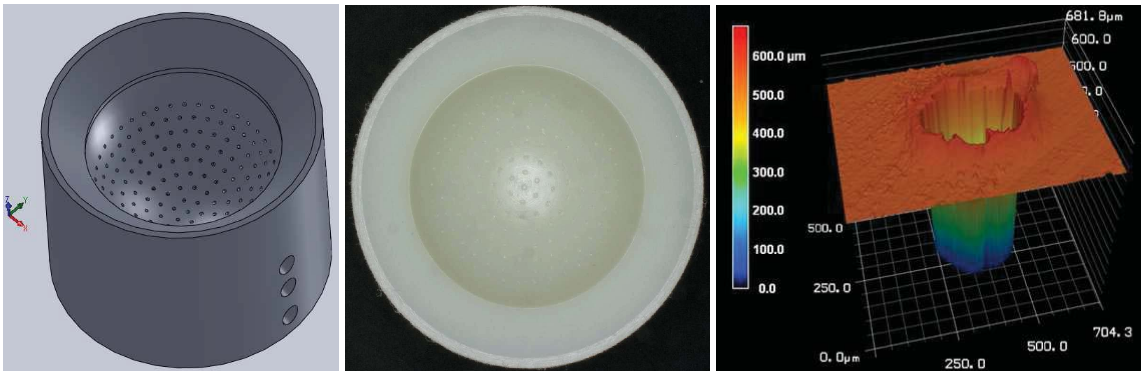
Previous measurements of frictional temperature rise on the surfaces of artificial joints have shown that temperature values could reach high levels that make hazardous effects on surrounding tissue and lubricant around the artificial joint [1,2,3]. In vivo measurement study Bergmann et al. recorded 43.1 ^{o}C temperature rise on the surface of hip prosthesis after one hour walking [4]. In [3] Lu and McKELLOP measured the temperature for UHMWPE acetabular cup as 40.4 ^{o}C under 2030 N loading and 6 hours test duration in vitro conditions. It is reported that if temperature rise reaches to 40^{o}C, formation of fibrous tissue may occur around the hip joint and this can induce periprosthetic pain and at the end failure of prosthesis [1,5]. For improvement tribological properties of conventional UHMWPE radiation-induced cross linking process was applied. The wear resistance was increased by cross-linking but oxidation resistance and mechanical properties were decreased because of the thermal treatments applied after the cross-linking process [6,7,8,9]. For reducing the problems aroused by the post-irradiation thermal treatment, α-tocopherol or vitamin E has been added in to the structure of UHMWPE as a natural antioxidant [10]. In previous studies it was reported that addition of vitamin E increases oxidation and delamination resistance of UHMWPE [11,12,13].

Besides materials structural properties, surface properties and lubrication of the sliding surfaces are also very important factors for reduction of frictional heating. Surface patterning is an effective method for obtaining better lubrication condition [14]. So it would be possible to decrease friction coefficient and temperature rise. Ito et al. formed concave dimples on CoCr alloy femoral head and they reported that surface dimples were served reduction abrasive wear of UHMWPE insert [15]. In another study Zhang et al. formed micro dimples on conventional UHMWPE disc samples and they concluded that wear and friction of UHMWPE decreased with surface dimples [14].

Previous studies focused on effect of surface dimples on wear and friction coefficient of conventional UHMWPE. Little literature research is available about frictional heating of VE-UHMWPE, actually there is no temperature rise measurement study about surface patterned VE-UHMWPE acetabular insert except our previous study [16]. In our previous studies we studied on frictional heating of 0,5 mm in diameter surface dimpled conventional UHMWPE and VE-UHMWPE [16, 17]. In this study we focused on determining effect of different dimple diameter on frictional heating. Also third body abrasive particle, loading and walking time effects were investigated.

II. Materials and Methods

Acetabular inserts were machined from Chirulen 1020 E rods (MediTECH Medical Polymers, Vreden, Germany). The inner surface of the samples were machined same as an acetabular insert and in accordance with ISO 7206-2:2011 and ISO 21535 [18,19]. To provide uniform construction for heat dissipation, metal backing or fixing tools were not used except screw to fix the samples. For this reason the outer surfaces of the samples were cylindrical in 40 mm diameter and three screws were used for fixation. Acetabular insert samples were divided in three groups. First group stayed as machined. 0.3 mm and 0.5 mm in diameter surface dimples were machined on second and third group's surfaces by five axis computer numerical control milling machine. CAD/CAM model of acetabular insert (a), manufactured acetabular insert sample (b), and microscopic image of 0,5 mm in diameter surface dimple (c) can be seen in fig.1.



a) b) c)

Figure 1. a) 3D CAD model of the acetabular cup with surface dimples and thermocouple holes, b) Manufactured acetabular insert, c) Microscopic image of 0,5 mm in diameter dimple.

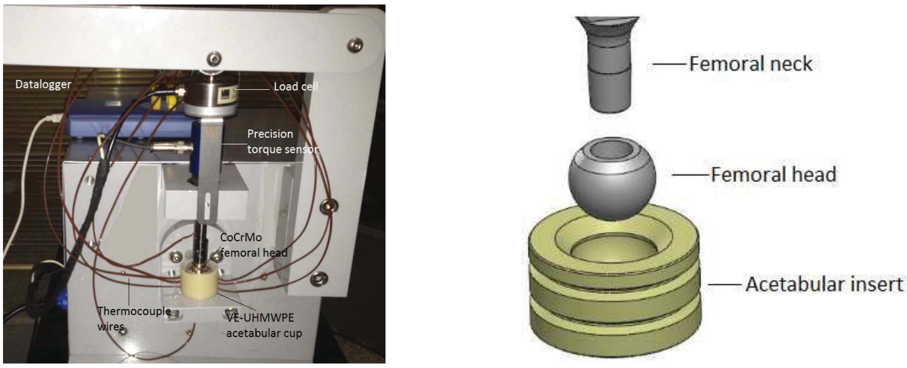
The acetabular cup samples were paired with CoCrMo commercially available femoral heads. The prostheses were in 28 mm diameter. Surface roughness of acetabular cups was measured by Taylor Hobson Form Talysurf Intra. The average surface roughness of vitamin E blended UHMWPE (VE-UHMWPE) was 0.647 µm. This value is suitable for the reference of ISO 7206-2:2011 [18]. Mechanical and thermal properties of VE-UHMWPE and CoCrMo can be seen in table 1.

Table 1. Mechanical and thermal properties of VE-UHMWPE and CoCrMo

Variable	Unit	VE-UHMWPE	CoCrMo
		Average	Average
Density	Kg/m^3	937	8270
Young's Modulus	MPa	683	200
Poisson's Ratio	-	0.46	0.3
Thermal Conductivity	W/(m*K)	0.4	12.1

Frictional measurements of the joints were carried out on a custom made hip joint friction simulator. For eliminating experimental inaccuracies the prosthesis were inverted with respect to anatomical position as in previous studies [2,3,20]. The experimental setup and configuration of acetabular insert and femoral head sample can be seen in figure 2. Temperature rise in acetabular and femoral component was measured with embedded thermocouples as shown in fig.2. Temperature measurements were taken from seven points in acetabular insert, and one point in femoral head. In this study only temperature rise of the central contact points of insert and head were evaluated with design of experiment. 3 mm diameter holes were drilled in to backside of the cups to 0.5 mm from the surface.

A standard Taguchi experimental plan with notation L9 (3^4) was chosen. The experimental results were transformed in to signal-to-noise (S/N) ratio as a quality characteristic to measure the deviation from desired values. In the analysis of S/N ratio there are three types of quality characteristic such as the-lower-the-better, the-higher-the-better and the-nominal-the–better [21]. In present study the-lower-the-better quality characteristic was chosen due to investigating the frictional heating of artificial joint materials.



(a) (b)

Figure 2. (a) Experimental setup (b) Configuration of acetabular cup, femoral head and femoral neck.

Control factors and their levels listed in table 2. 750 N, 1000N and 1500 N static loads were applied for representing different body weights. In flexion-extension plane, a simple harmonic oscillatory motion between $\pm 24^{o}$ is applied to the acetabular component. The period of motion was 1 Hz and the tests were run up to 1, 2 and 3 hours for simulating different walking durations. 5 ml, 25% Bovine Calf (Sigma-Aldrich) serum was used as lubricant. To avoid bacterial contamination 0.3% sodium azide and 5 mM EDTA was added in to the lubricant. The viscosity of the lubricant measured with NDJ-1 Rotary Viscometer as 0.002 Pa.s

Table 2. Control factors and their levels

Level	Factors			
	Surface	Load (N)	PMMA (mg)	Time (h)
1	unpatterned	750	0	1
2	0.3 mm patterned	1000	25	2
3	0.5 mm patterned	1500	50	3
Factor code	A	B	C	D

III. Results and Discussion

Taguchi's experimental layout and measured frictional temperature rises were presented in table 3. Each experiment was repeated three times for each condition. Temperature values were recorded for each cyle. The data logger program gives the temperature values with two digits after the decimal point and the results were not rounded up or down, they presented as recorded form. Also the signal-to-noise (S/N) ratios, calculated for the-lower-the-better quality characteristic, can be seen in table3.

Table 3. Experimental layout and results with calculated S/N ratios

Experiment no	**Factor Codes and Levels**				**Frictional temperature rise (°C) for VE-UHMWPE**			
	A	**B**	**C**	**D**				
					ΔT_1	**ΔT_2**	**ΔT_3**	**S/N**
1	0	750	0	1	7.49	7.61	7.72	-17.6245
2	0	1000	25	2	10.79	10.83	10.91	-20.7033
3	0	1500	50	3	14.16	14.26	14.22	-23.0540
4	0,3	750	25	3	6.12	6.31	6.19	-15.8579
5	0,3	1000	50	1	4.44	4.62	4.51	-13.1103
6	0,3	1500	0	2	6.90	7.15	7.09	-16.9607
7	0,5	750	50	2	7.06	7.35	7.12	-17.1198
8	0,5	1000	0	3	7.72	7.98	7.79	-17.8761
9	0,5	1500	25	1	9.61	9.84	9.68	-19.7448

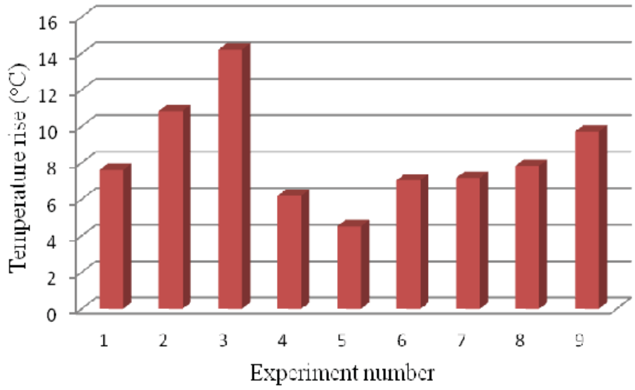


Figure 3. Average temperature rise of VE-UHMWPE acetabular cups for each experiment condition.

As can be seen from table 3 and fig. 3 frictional temperature rise increased by increasing applied load, amount of PMMA and sliding time. By increasing static load contact points between the sliding surfaces were increased. So the lubricant couldn't reach the contact area and the surface could not be cooled enough. Therefore frictional heating of the surfaces were increased. Adding of PMMA caused to increase in friction coefficient and temperature rise between the surfaces. PMMA particles scratched the surface of both acetabular insert and femoral head and caused third body abrasive wear [APMAS]. So temperature rise increased while the surface quality decreased.

Surface patterning reduced frictional temperature rise of the surfaces. In our previous study we reported that 0,5 mm in diameter surface dimples reduced the frictional heating of conventional UHMWPE and VE-UHMWPE acetabular insert and CoCrMo femoral head. As can be seen in fig.3 the minimum temperature rises were recorded for 0,3 mm in diameter patterned samples for VE-UHMWPE acetabular insert like as conventional UHMWPE [17]. The highest temperature values were recorded for unpatterned samples. Surface dimples acted as reservoir for lubricant and stored it in. So the dimples provided extra lubricant source and enhanced the lubrication condition for sliding surfaces. Also PMMA particles were captured inside the dimples so third body abrasive effects of the particles were decreased. In unpatterned insert surfaces PMMA particles scratched the surface and embedded in it (fig.4) [14].

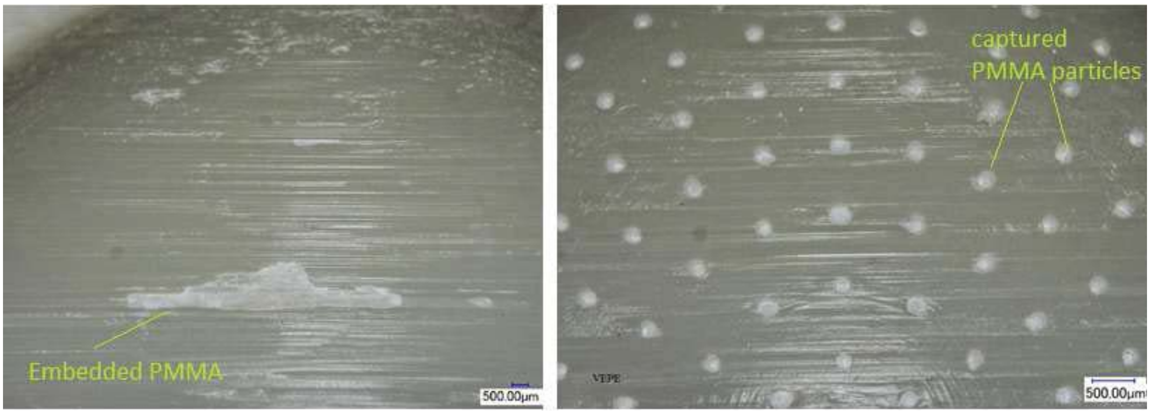


Figure 4. Inner surface of unpatterned (a), patterned VE-UHMWPE insert (b)

It is clear from the main effects plots for S/N ratios in fig.5, the optimal process parameters for minimum temperature rise as A2B1C1D1 for the-lower-the-better quality characteristic. That means the minimum temperature value would be recorded while the surface dimple diameter was 0,3 mm, the applied load was 750 N, the amount of PMMA was 0 mg and the walking time was 1 hour. For verifying the obtained parameter values, confirmation tests were conducted by using these parameters. The predicted temperature rise value by Taguchi model was 2,64 ^{o}C. After three experiments the average measured temperature rise value was 3,98 ^{o}C. Both these values were lower than the values in experimental design. So it can be concluded that the defined parameters are optimal parameters for temperature rise measurements.

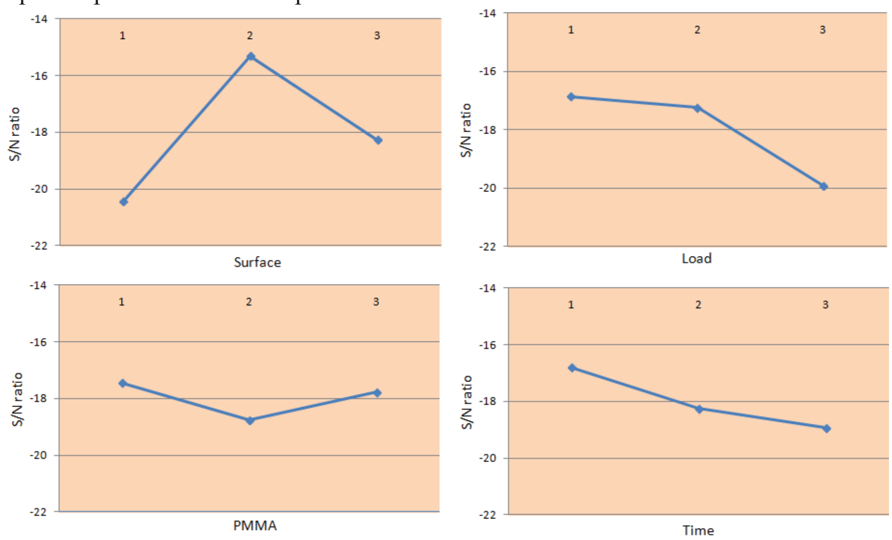


Figure 5. Main effects plot for S/N ratios for VE-UHMWPE

By applying analysis of variance the statistically significance of parameters were determined. For 95% confidence level, the degree of freedom for factors was 2 and for error was 18. So the F value read from the table for each factor was; F_{table} 0.05 (2, 18) = 3,55. The calculated *F* values for design parameters and contribution of each parameter to the results can be seen in table 4. The calculated F value for surface factor was 4563,41, for load was 2260,20, for PMMA was 421,79 and for time was 844,80. Because the calculated F values were higher than F_{table}, all of the factors have significant effect on the frictional heating of VE-UHMWPE acetabular insert.

Table 4. Analysis of variance table

Factors	Sum of squares (SS)	Variance (V)	F value	Contribution ratio (%)
Surface	110.975	55.488	4563.41	56.3436
Load(N)	54.965	27.482	2260.20	27.9065
PMMA (mg)	10.257	5.129	421.79	5.20763
Time (h)	20.544	10.272	844.80	10.4305
Error	0.219	0.012		0.11119
Total	196.961			

Temperature rise of CoCrMo femoral heads were higher than VE-UHMWPE acetabular inserts. Thermal conductivity of CoCrMo is 12,1 W/m.K and of VE-UHMWPE is 0,4 W/m.K (table 1). So huge portion of the frictional heat conducted inside the femoral head.
In our previous study we reported frictional heating behavior of conventional UHMWPE according the Tagucgi's experimental design [17]. Temperature values for conventional UHMWPE were a bit higher than VE-UHMWPE in same experiment conditions. For comparison of acetabular insert materials frictional heating behaviors the experiments are going on with highly cross-linked UHMWPE and vitamin E blended highly cross-linked UHMWPE.

VI. Conclusions

Frictional temperature rise on the surfaces of artificial joints could reach high levels that make hazardous effects on surrounding tissue and lubricant around the artificial joint. So it is important to define frictional temperature rise of artificial joint materials and take some precautions for reduction of heating. In this study acetabular insert samples, manufactured with surface dimple were tested according to Taguchi experimental design and optimal testing parameters were investigated. It can be concluded that;

- The surface dimples served to reduce frictional heating by providing better lubrication.
- With better lubrication friction coefficient was decreased.
- Frictional temperature rises were increased by increasing applied static load,
- Addition of PMMA raised the frictional temperature rise and scratched the surface of the acetabular insert.
- Taguchi experimental design and analysis of variance results showed that, surface patterning, loading, amount of PMMA and test duration parameters have significant effect on the frictional heating of UHMWPE acetabular insert.

VII. Acknowledgments

This research has been supported by Yildiz Technical University Scientific Research Projects Coordination Department. Project Number : 2011-06-01-DOP03.
The authors would like to thank to Interchangeable Manufacturing and Industrial Metrology and Nanometrology Laboratory at the Vienna University of Technology, Wien,Austria, for support of surface measurements and to MediTECH Medical Polymers, (Vreden, Germany) for material support of the study.

References

[1] C.C. Hu, J.J. Liau, C.Y. Lung, C.H. Huang, C.K. Cheng, "A two dimensional finite element model for frictional heating analysis of total hip prosthesis", *Materials Science and Engineering C,* 17, pp. 11–18, 2001.
[2] Y.-S. Liao, H. McKellop, Z. Lu, P. Campbell, P. Benya, "The effect of frictional heating and forced cooling on the serum lubricant and wear of UHMW polyethylene cups against cobalt–chromium and zirconia balls", *Biomaterials,* 24, pp. 3047–3059, 2003.
[3] Z.Lu and H. McKellop, "Frictional heating of bearing materials tested in a hip joint wear simulator", *Proceedings of the Institution of Mechanical Engineers Part H Journal of Engineering in Medicine,* 211, pp. 101-108, 1997 .

[4] G. Bergmann, F. Graichen, A. Rohlmann, N. Verdonschot, G.H. Van Lenthe, Frictional heating of total hip implants Part 1: measurements in patients, *Journal of Biomechanics* 34, pp. 421–428, 2001.
[5] G. Bergmann, F. Graichen, A. Rohlmann, N. Verdonschot, G.H. Van Lenthe, "Frictional heating of total hip implants Part 2: Finite element study", *Journal of Biomechanics,* 34, pp. 429–435, 2001.
[6] H. Bhatt and T. Goswami, Implant wear mechanisms—basic approach, Biomedical Materials 3,1-9, 2008.
[7] C.A. Jacobs, C.P. Christensen, A.S. Greenwald, H. McKellop, Clinical Performance of Highly Cross-Linked Polyethylenes in Total Hip Arthroplasty, *The Journal of Bone & Joint Surgery Am*, 89, 2779-2786, 2007.
[8] L. Bradford, D.A. Baker, J. Graham, A. Chawan, , M.D. Ries, L.A. Pruitt, Wear and surface cracking in early retrieved highly cross-linked polyethylene acetabular liners, *The Journal of Bone & Joint Surgery*, 86, 1271-1282, 2004.
[9] J. Furmanski, S. Gupta, A. Chawan, A. Kohm, J. Lannutti, B. Jewett, L.A. Pruitt, M.D. Ries, Aspherical femoral head with highly cross-linked ultra-high molecular weight polyethylene surface cracking, *The Journal of Bone and Joint Surgery,* 89, 2266-2270, 2007.
[10] C. Vaidya, E. Alvarez, J. Vinciguerra, D. A. Bruce, J. D. DesJardins, Reduction of total knee replacement wear with vitamin E blended highly cross-linked ultra-high molecular weight polyethylene, *Proceedings of the Institution of Mechanical Engineers Part H Journal of Engineering in Medicine* 225, 1-7, 2011.
[11] P. Bracco, E. Oral, Vitamin E-stabilized UHMWPE for Total Joint Implants, *Clinical Orthopaedics and Related Research,* 469, 2286–2293, 2011.
[12] E. Oral, S.L. Rowell, O.K. Muratoglu, The effect of α-tocopherol on the oxidation and free radical decay in irradiated UHMWPE, Biomaterials 27, 5580-5587, 2006.
[13] E. Oral, K.K. Wannomae, N.E. Hawkins, W.H. Harris, O.K. Muratoglu, α-Tocopherol doped irradiated UHMWPE for high fatigue resistance and low wear, *Biomaterials* 25, 5515-5522, 2004.
[14] B. Zhang, W. Huang, X., Wang, "Biomimetic surface design for ultrahigh molecular weight polyethylene to improve the tribological properties", *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 0(0): 1-9, 2012.
[15] H. Ito, K. Kaneda T. Yuhta, I. Nishimura, K. Yasuda, T. Matsuno, "Reduction of polyethylene wear by concave dimples on the frictional surface in artificial hip joints", *The Journal of Arthroplasty*,15(3), 332-338, 2000.
[16] B.Sagbas, M.N Durakbasa, "Effect of surface patterning on frictional heating of vitamin E blended UHMWPE" *Wear*, 303(1-2), 313-320 (2013).
[17] B.Sagbas, M.N Durakbasa, "Investigating Effects of Testing Parameters on Frictional Heating of UHMWPE by Taguchi Method", 3rd International Advances in Applied Physics and Materials Science Congress, 24-28 April 2013, Antalya, Turkiye.
[18] ISO 7206-2:2011, Implants for surgery-Partial and total hip joint prostheses Part 2: Articulating surfaces made of metallic, ceramic and plastics materials.
[19] ISO 21535:2001 Non-active surgical implants-Joint replacement implants - Specific requirements for hip-joint replacement implants.
[20] Y. Yan, A. Neville, D. Dowson, S. Williams, J. Fisher, "Effect of metallic nanoparticles on the biotribocorrosion behavior of Metal-on-Metal hip prostheses", *Wear* 267, pp. 683–688, 2009.
[21] M. Sirvancı, *Kalite için Deney Tasarımı Taguçi Yakla*sımı, _stanbul, Literatür Yayıncılık, 1997.