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Effect of Radial Clearance, Corner Radius and Micro-Lateralization on Contact Stress of Metallic and Ceramic Hip Prosthesis – A Finite Element Analysis

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ABSTRACT

Edge loading leads to high contact stress at the rim of the contact. This is due to less radial clearance and excessive lateral head displacement which potentially causes implant failure. The ceramic implants have a high possibility of fracture compared with metallic implants because of above-said reasons. The present study focuses on the investigation of contact stress for the combined effect of radial clearance (0.05-0.75 mm) and micro-lateralisation conditions (1-2.5 mm) for Metal-on-Metal (M-o-M) and Ceramic-on-Ceramic (C-o-C) pairs. The contact stresses are analysed for round corners of the acetabulum cup geometry for the above-said combinations with four different arc radii (1- 4mm). Finite element modeling (FEM) of femur head with half of the acetabulum cup is considered for the current study. Contact stress values obtained for 2 mm and 4 mm round corner geometry are quite low when compared with 1 and 3 mm round corners even for larger radial clearances and high lateral head displacements. The study also showed von Mises stress value obtained for M-o-M pair is quite low for 4 mm round corner for larger radial clearance and high lateral head displacements. Similarly, in C-o-C pair the compressive stress values are minimum for 4 mm round corner. Since the stress values were minimum for 4 mm round corner geometry, it clearly indicates that even edge loading occurs and the round corner geometry would be very helpful in reducing the stress for both M-o-M and C-o-C pairs.

Keywords: Contact stresses; Radial clearance; Micro-lateralisation; Finite element analysis; Hip prosthesis

1. INTRODUCTION

Osteolysis and high wear of polyethylene had led to the use of Metal-on-Metal (MoM) hip implants which showed lesser wear rate and low friction compared with Metal-on-polyethylene (M-o-P)[1]. In-Vivo studies showed the effect of metal ions which released into the bloodstream led to tissue related problems and aseptic loosening[2]. At present, C-o-C pairs are used as an alternative to M-o-M in hip replacement due to the lesser wear rate of the former pairs[3]. Silicon Nitride ceramic material also showed lower wear rate which is closer to the alumina bearing couple[4].

Micro-lateralisation phenomenon is causing surface damage and inducing high stress which was mainly due to lesser radial clearance and implant malpositioning. This micro-lateralisation leads to edge loading and causes stripe wear on the head[5]. The effect of microseparation causing severe wear of alumina-zirconia pair was investigated for 5 million cycles using a hip simulator[6]. The edge loading led to an increase in contact stress which was developed at the edge of the cup. Another study[7] investigated the wear of ceramic composites under microseparation condition for 5 million cycles using a hip simulator. The size of wear particles for M-o-M pairs using a hip simulator was quite large in size under microseparation condition when compared with the wear particles under no microseparation condition[8]. Finite Element Analysis (FEA) study helps in analysing contact stress and wear of hip implants with the help of FEA tool[9-10]. Another study[9] showed that the lateral head displacement of greater than 0.1 mm could lead to high contact stresses in M-o-M. Another study[11] analysed the contact mechanics of C-o-C combination under microseparation and showed that higher contact stress was observed for larger microseparation i.e. lateral head displacement leading to edge contact. Influence of radial clearance between the head and cup plays a significant role to lubricate the implants, and mainly larger diametric clearances were preferred for better lubrication[12]. Another recent literature studied the effect of ellipsoidal geometry in reducing the stress. Interestingly ellipsoidal geometry found to have significant effect in reducing the stress over conventional geometry design[13]. The head lateral displacement is found to be the major factor affecting the failure of the implants due to increased stress concentration affecting the implants as edge contact occurs. The literatures focused on analyzing edge loading with combined effect of radial clearance, round corner and head lateral displacement were not analysed in detail so far.

The main aim of this article is to analyse the combined effect of radial clearance and micro-lateralisation in C-o-C and

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M-o-M bearings which influence the contact stresses using FEA for circular geometry of acetabulum cup. No literature focused on analyzing the contact stress developed by varying the radial clearance for different lateral head displacements as well as for round corner geometries. The micro-lateralisation values are varied from 1 mm - 2.5 mm. Radial clearance values are varied from 0.05 mm - 0.75 mm and the circular arc for round corner geometry of acetabulum cup varied from 1 mm - 4 mm. For each fixed radial clearance values, round corner geometry and micro-lateralisation values are varied, and the resulting contact stress values are plotted.

2. METHODOLOGY

The 3D finite element model was developed using ANSYS software, as shown in Fig.1. The entire model is meshed with tetragonal elements using SOLID 186 element. Mesh refinements were made at the contact regions of femur head and acetabulum cup. A suitable mesh convergence study was performed, and the element size of 1 mm at the contact interface and 2 mm for remaining regions are chosen which generated a total of 68,524 elements and 88,434 nodes. The contact between the head and cup surface is established using CONTA 174 and TARGE 170 elements. For the present study, only half of the cup is modeled. The acetabulum cup is positioned at 45°and the anti-version angle is kept at 0°. The effect of pelvic bone had a negligible effect on contact stresses [14]. Therefore the present study ignored the modeling of the pelvic bone. The acetabulum cup thickness of 8 mm and the diameter of the femur head as 36 mm is considered for the present study[15]. The head and cup are modeled as Co-Cr (M-o-M) pair and Si_3N_4 ceramic material (C-o-C). The Young's modulus of Si_3N_4 and Co-Cr bearing couple are 300GPa and 210GPa, Poisson's ratio is taken as 0.29 and 0.3, and the friction coefficient is considered as 0.2 and 0.09 respectively for Si_3N_4 and Co-Cr[4,15-16]. The outer surface of the acetabulum cup is constrained in all directions which means that the displacement in all three directions is set to zero. A constant vertical load of 3 kN is considered for this study. Since only half of the acetabulum cup is modeled, gait load of 1.5kN is applied at the center node of the femur head[15].

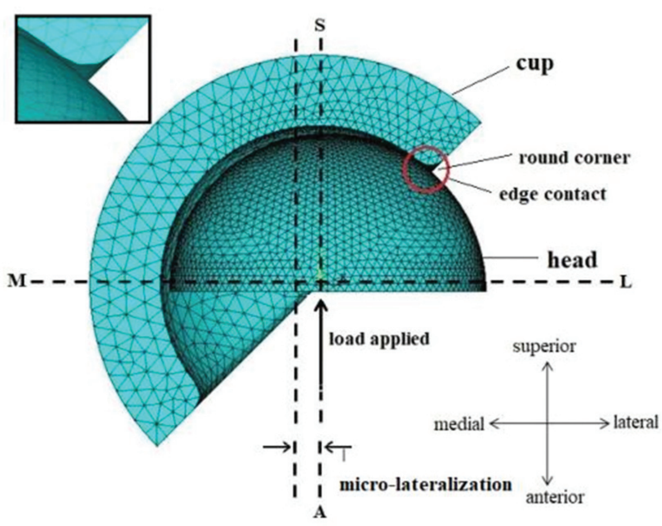


Figure 1. Finite element model with round corner acetabulum cup.

Larger radial clearance values are preferred for better lubrication, and it also reduces edge loading, but previous literatures[15,17] preferred smaller radial clearance and ignored larger radial clearance values which influences contact stresses. The different radial clearance values considered for the current study are 0.05 mm, 0.1 mm, 0.5 mm and 0.75 mm respectively[18]. Since mild and severe micro-lateralisation values showed an increased wear rate and linear wear of the bearing is mainly influenced by contact stresses in FEA, above micro-lateralisation values are considered[15,17].

3. RESULTS AND DISCUSSIONS

3.1 Contact Stress Analysis of Round Corner M-o-M

The contact stress is analysed for four different fillet radii against various head lateralisation and radial clearance values. The contact stress plot for some selected fillet radii against small and larger radial clearance values for four different lateral head displacements are shown in Fig. 2. Of all the cases considered, minimum contact stress of 0.3 GPa is found for 0.05 mm radial clearance with lateral head displacement value of 1 mm having a fillet radius of 4 mm. While maximum contacts stress value of 1.12 GPa is obtained for 0.75 mm radial clearance with the micro-lateralisation value of 1.5 mm having a fillet radius of 1 mm. The red colour in the Fig. 2 indicates the maximum value and blue colour indicates minimum value of stress. Contact stress values comparison for different round corner geometries is shown in Fig.3. In general, increasing the radial clearance for various lateral head displacements led to increased contact stresses. For radial clearances of 0.5 mm and 0.75 mm, the contact stress values get reduced for some selected lateral head displacements and then increases. This kind of reduction and increase in contact stress phenomenon is reported in the previous literature[15]. Maximum contact stress in each round corner geometry is found to be 1.12 GPa, 0.88 GPa, 0.96 GPa and 0.81 GPa for 1 mm, 2 mm, 3 mm and 4 mm round corners respectively. The percentage reduction in contact stresses when compared with 1 mm circular arc is found to be 21.42 per cent, 14.28 per cent and 27.67 per cent for 2 mm, 3 mm and 4 mm round corners respectively. On comparing the percentage reduction in contact stress values in minimum and maximum categories, 4 mm round corner geometry showed a greater reduction in contact stress.

3.2 Contact Stress Analysis of Round Corner C-o-C

Contact stress comparison plot of C-o-C bearing is shown in Fig. 4. Overall, minimum contact stress of 0.32 GPa is obtained for a fillet radius of 4 mm having a radial clearance of 0.05 mm with lateral head displacement of 1 mm. While, maximum contact stress of 1.18 GPa is obtained for a round corner 1 mm with a radial clearance of 0.75 mm having a lateral head displacement of 1.5 mm. In all the cases, C-o-C pair showed higher contact stress values compared with M-o-M. For C-o-C pairs, minimum contact stress values for each round corner geometry are 0.61 GPa, 0.39 GPa, 0.41 GPa and 0.32 GPa for 1, 2, 3 and 4 mm fillet radius respectively. The

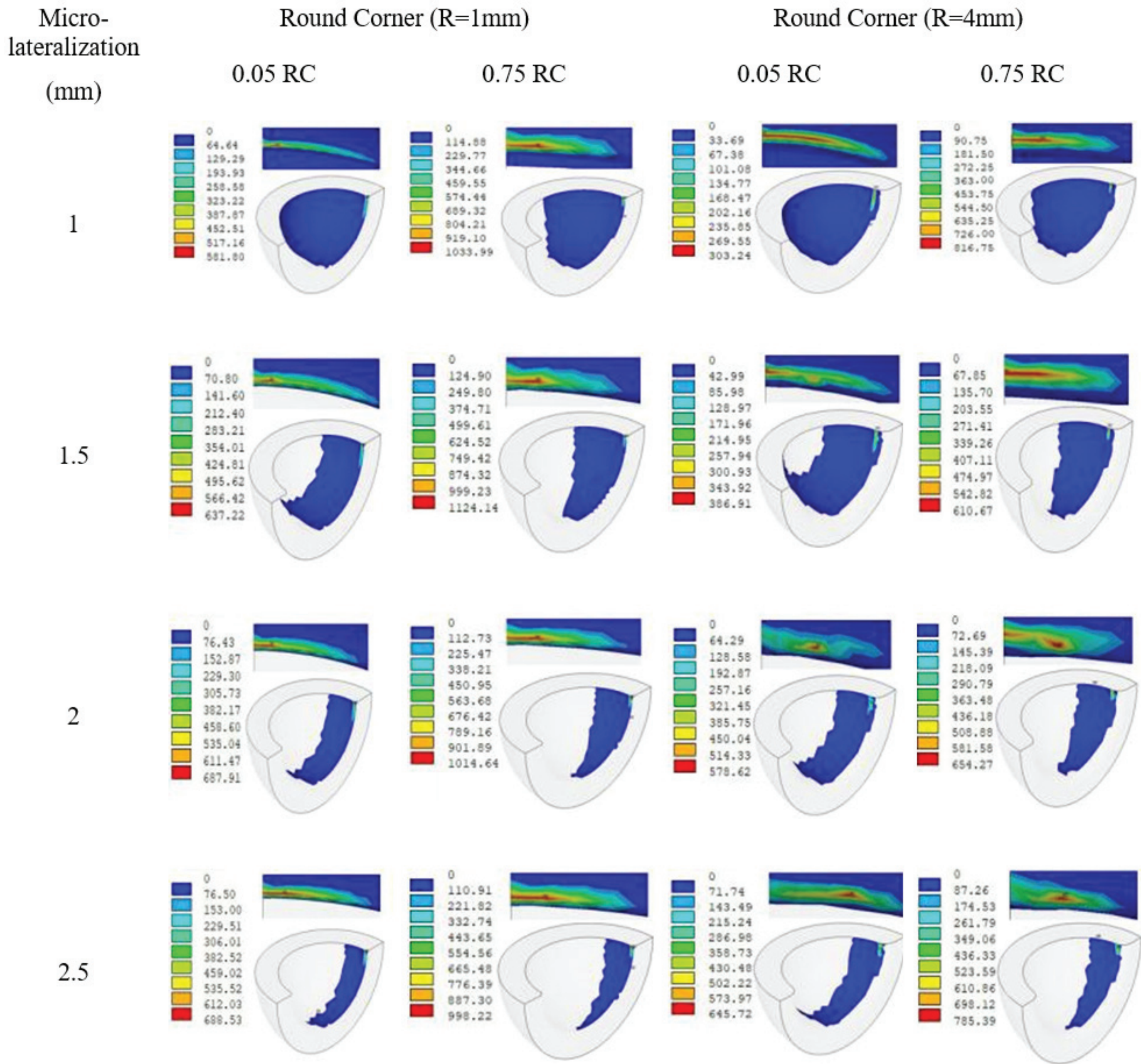


Figure 2. Contact stress (MPa) plot for M-O-M pair.

percentage reductions in contact stress when compared with 1 mm arc radius are 36.06 per cent, 32.78 per cent, and 47.54 per cent respectively for 2, 3 and 4 mm round corner geometries. Maximum contact stress values are found to be 1.18 GPa, 0.91 GPa, 1.11 GPa, and 0.89 GPa respectively for 1, 2, 3 and 4 mm round corner geometries. From these results, it is also evident that increasing fillet radius showed a significant reduction in contact stress values. From the above comparisons, 4 mm round corner had a better reduction in contact stress. The comparison of these contact stress values is shown in Fig. 4.

3.3 Von Mises Stress Analysis of M-o-M

Von Mises stress comparison plot for M-o-M is shown in Fig. 5. Overall, the maximum von Mises stress value of 1.20 GPa is obtained for 2 mm fillet radius with 0.75 mm radial clearance having lateral head displacement of 2.5 mm. Minimum stress value of 0.35 GPa is obtained for 2 mm fillet radius with 0.1 mm radial clearance having lateral head displacement of 1mm. On comparing the maximum von Mises stress, the percentage reduction in stress values are of 2.08 per cent and 4.16 per cent for 3 mm and 4 mm round corner geometry, while, 2 mm fillet radius showed 25 per cent increase in stress. From the comparison stress plot for four round corner geometries as shown in Fig. 5.it is quite clear that 4 mm round corner geometry showed yield stress values quite closer to 0.82 GPa which is reported to be the yield strength of CoCr alloy[9]. The von Mises stress values obtained from the current study with 0.05 mm radial clearance for 1 mm round corner geometry is quite similar to that of the previous literature[15] and it increases with increase in lateral head displacement values.

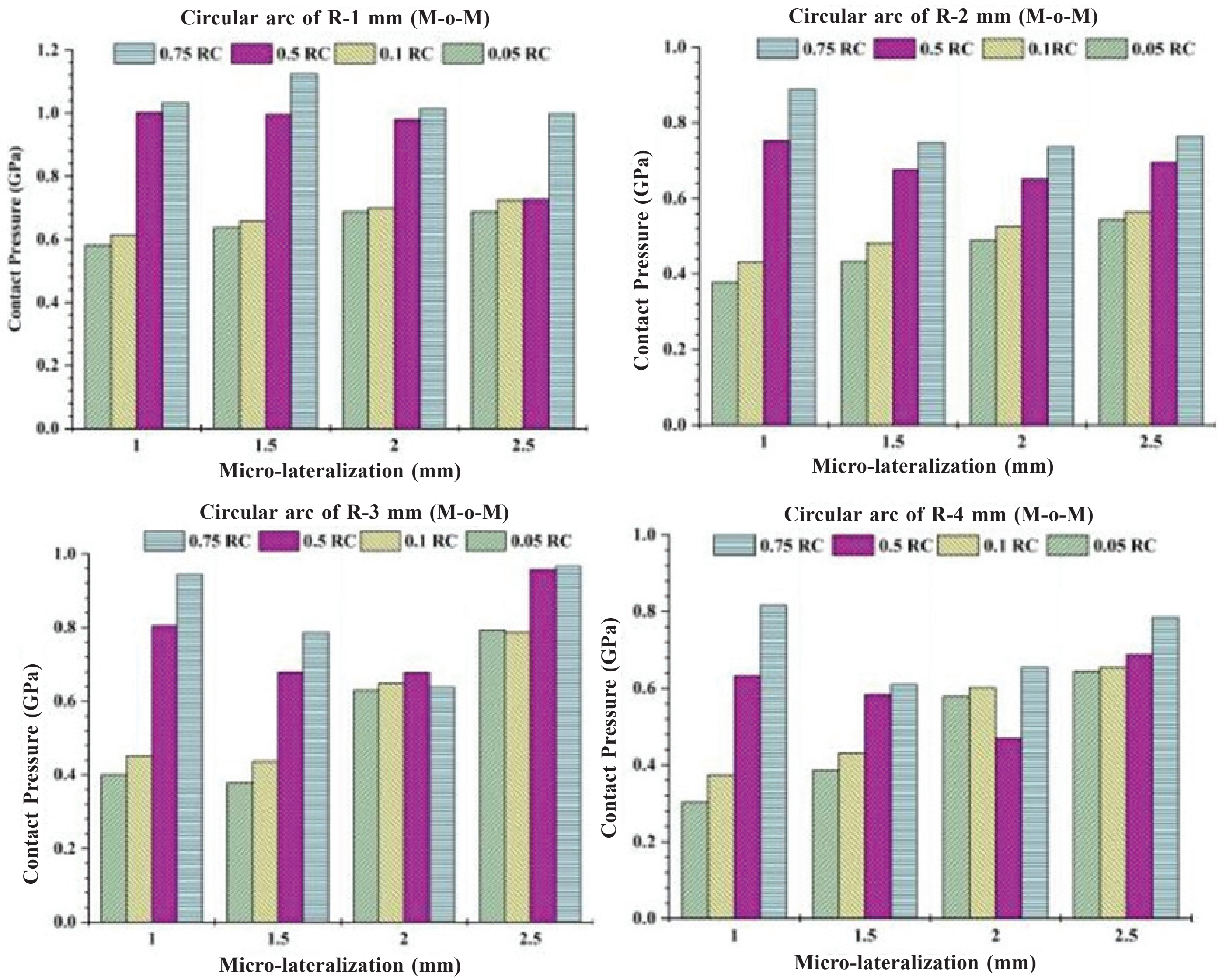


Figure 3. Contact stress comparison of M-O-M for four round corner geometries.

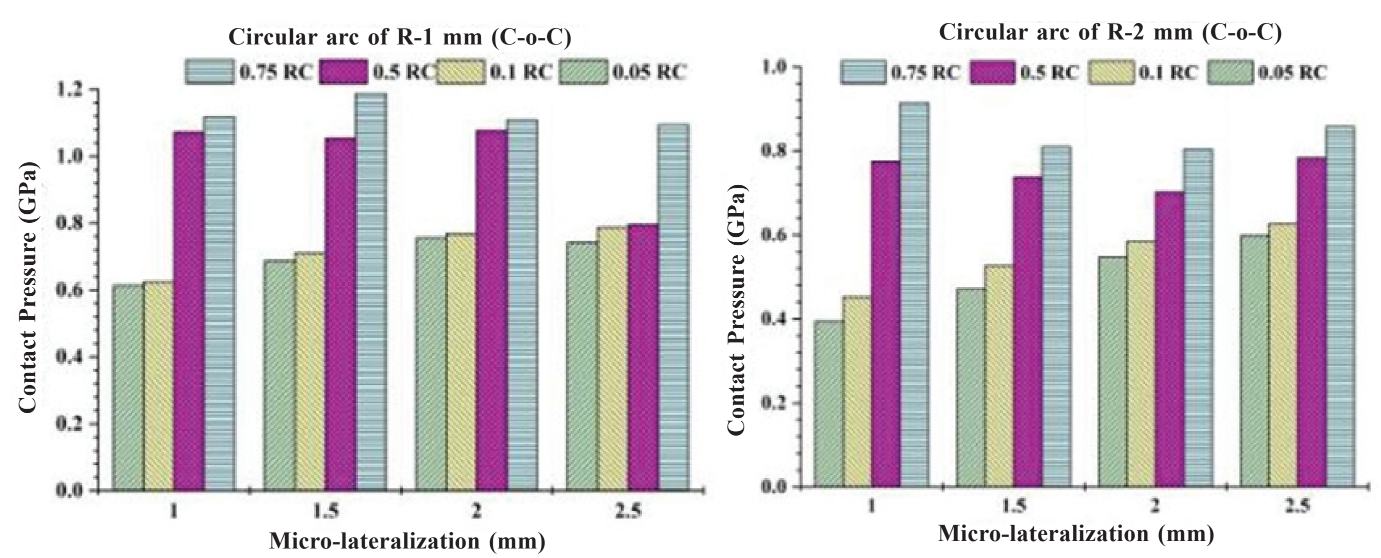


Figure 4. Contact stress comparison of C-O-C for four round corner geometries.

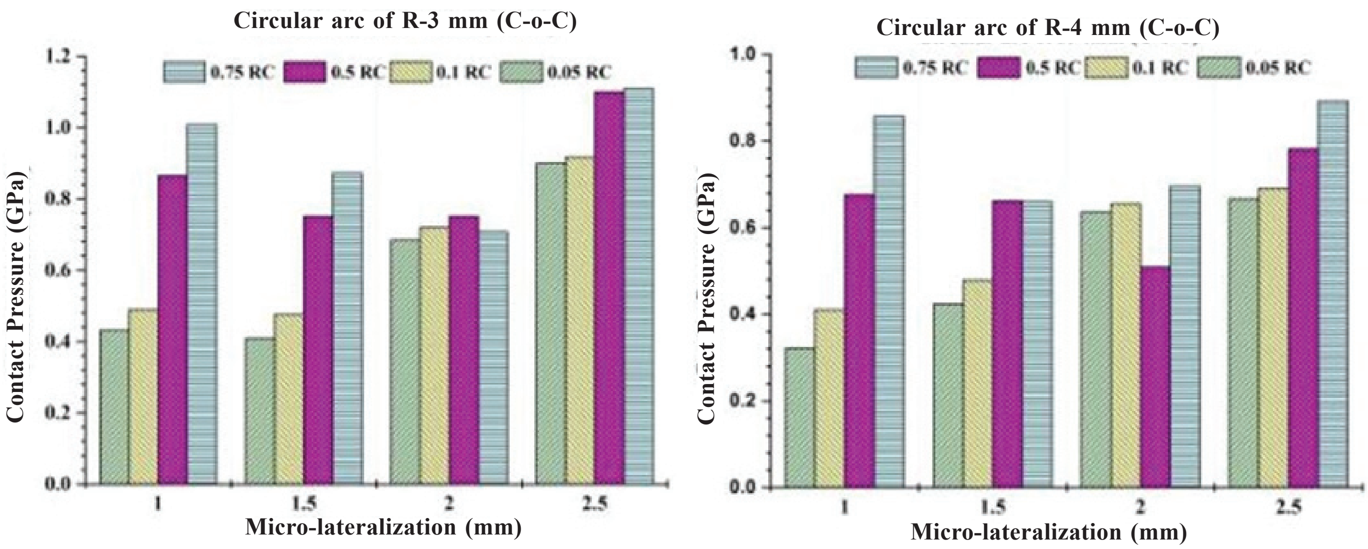


Figure 4. Contact stress comparison of C-O-C for four round corner geometries.

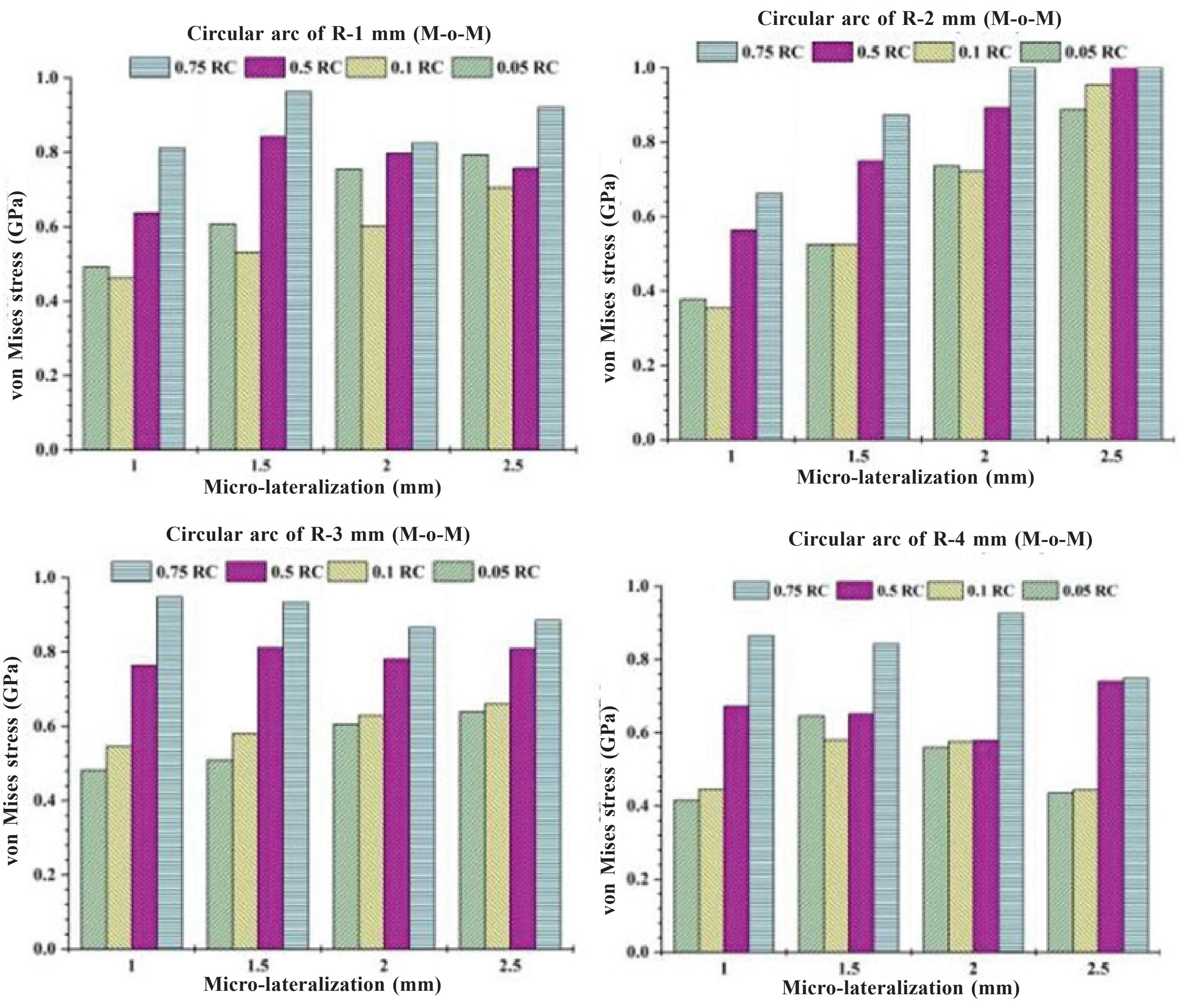


Figure 5. von Mises stress comparison of M-O-M for four round corner geometries.

3.4 Compressive Stress Analysis of C-o-C

Since ceramic materials do not show ductility behaviour, the present study compared the maximum compressive stress developed for C-o-C pairs. Overall, for 1 mm arc radius, the maximum compressive stress of 1.75 GPa and 0.52 GPa is obtained for 4 mm arc radius. These values correspond to 0.75 and 0.05 mm radial clearances which having a lateral head displacement of 1.5 and 1mm. On comparing the maximum compressive stress values with 1 mm round corner, 7.47 per cent, 25.28 per cent and 29.31 per cent reduction in stress values are noted for 2, 3 and 4 mm round corner geometries. Comparison of compressive stress values concerning different

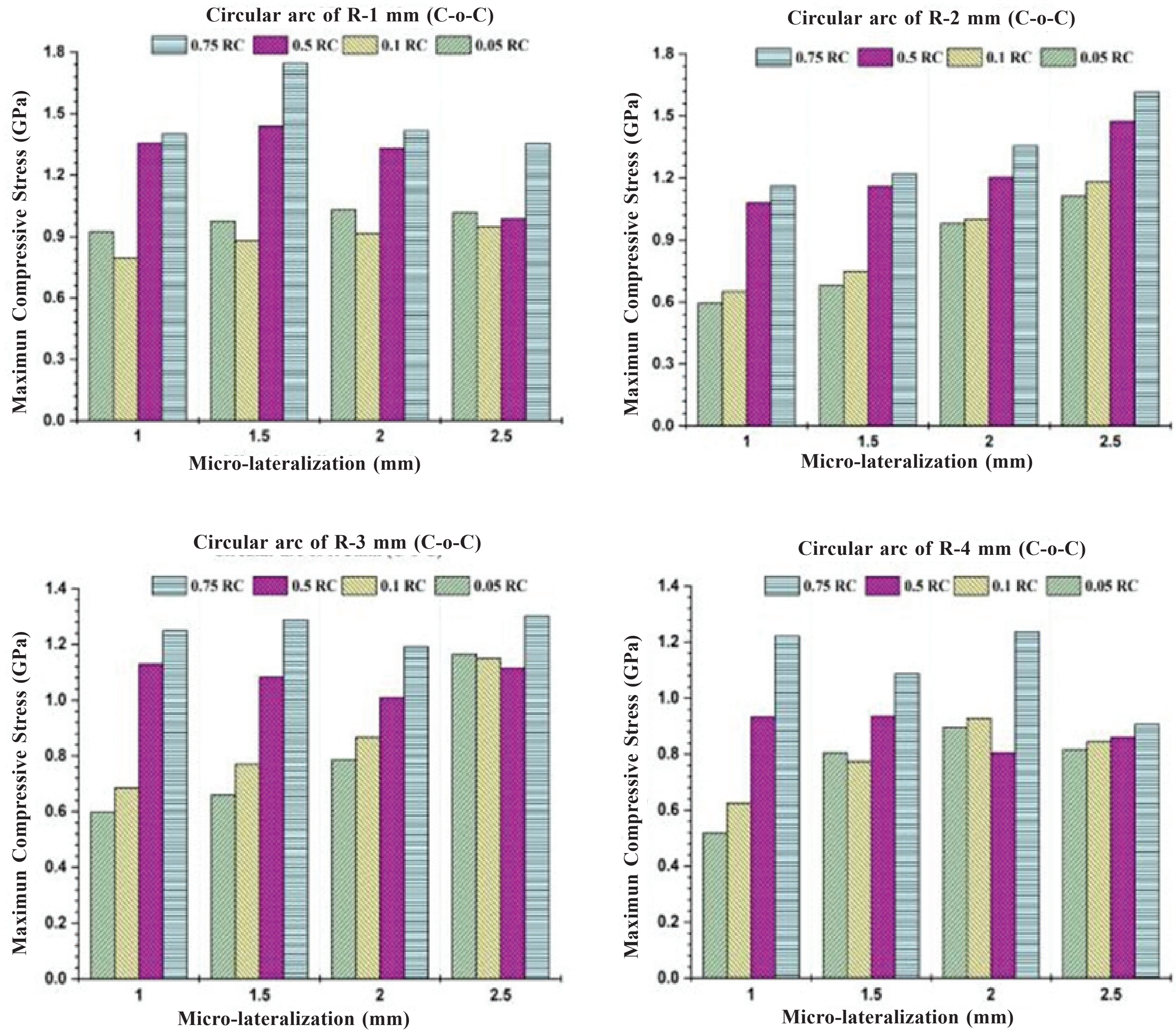


Figure 6. Maximum compressive stress comparison for C-o-C pairs.

Table 1. Parameters analyzed for current study

Combination	Parameters	Analysis	Findings
M-o-M (Co-Cr)	Micro-lateralization, Radial Clearance, Circular cup radius	Contact Pressure, von Mises Stress	Round corner 4 mm showed better reduction of stress for large radial clearances with 1 mm head lateral displacement
C-o-C (Si_3N_4)	Micro-lateralization, Radial Clearance, Circular cup radius	Contact Pressure, Compressive stress	Round corner 4 mm showed better reduction of stress for large radial clearances and maximum head lateral displacement

lateral head displacements and radial clearances for C-o-C pair are shown in Fig. 6. From these results, it is quite evident that 4 mm round corner geometry plays a major role in reducing the compressive stress.

4. DISCUSSION

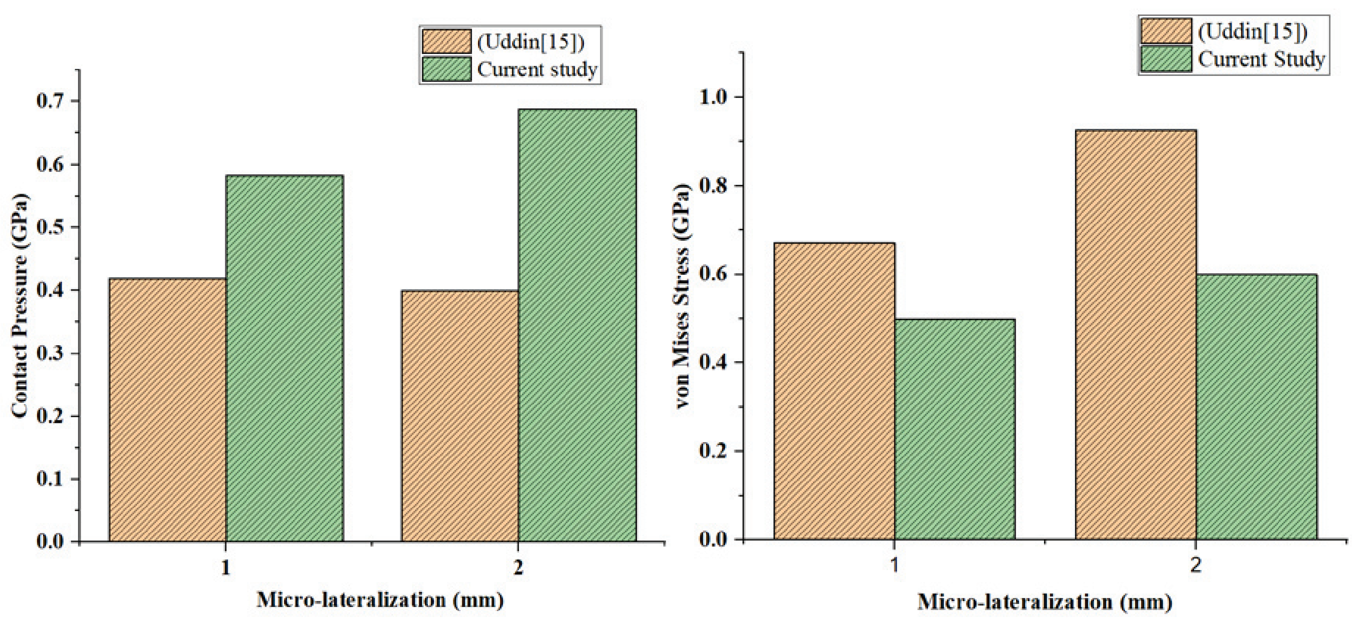
While comparing the contact stress developed for M-o-M and C-o-C pairs, the following observations are made. Contact stress values generated for M-o-M are found to be lower than the C-o-C pair, which is observed while comparing both maximum and minimum contact stress values obtained in four round corner geometries. The reason behind the increase in contact stress values for C-o-C might be due to the higher modulus of elasticity when compared with the metallic pairs. From the contact stress plot, both for M-o-M and C-o-C, it is evident that increasing the radial clearance resulted in a wider distribution of contact stresses.For sharp corner geometry having 1 mm micro-lateralisation, the contact stress value of 0.84 GPa for 0.05 mm radial clearance[15] is obtained for M-o-M. While comparing the sharp corner[15] with the current study of round geometry of 4 mm, which showed contact stress value of 0.30 GPa, the percentage reduction in contact stress values are found to be 64.28 per cent. Also, the previous literature[15] reported contact stress values as 0.41 GPa for 1 mm lateral head displacement with 0.05 mm radial clearance for 1 mm arc radius. On comparing the above stress values with the present study for 4 mm round corner, the percentage reduction in contact stress value is found to be 26.82 per cent. From this comparison, it is also evident that increasing fillet radius showed a huge reduction in contact stresses.

Figure 7 shows the comparison of results with current study and literature results. von Mises stress for M-o-M with 1 mm round corner for 0.05 mm radial clearance and 1 mm lateral head displacement was 0.66 GPa[15]. However, for sharp corner geometry, the stress value was found to be 0.79GPa[15]. On comparing the round corner and sharp corner the yield stress values[15] with the present study for round corner 4 mm radius, which showed stress value 0.41 GPa, the percentage reduction in stress values are 37.87 per cent and 48.10 per cent. Quite high reductions in yield stress values are noted. The strength of Si_3N_4 ceramic material is found to be in the range of 0.95 GPa to 1.2 GPa[4]. From compressive stress values graph for C-o-C pair, it could be identified that the stress values lies within the strength of silicon nitride ceramic material for 4 mm round corner geometry. Therefore for larger radial clearance and high lateral head displacements, it is advisable to use 4 mm round corner geometry for C-o-C pairs.

5. CONCLUSIONS

The contact stress developed for four round corner geometries of M-o-M and C-o-C pairs with a combination of micro-lateralisation and radial clearance is analysed using the FE model. The following conclusions are made.

The contact stress values are found to be higher for C-o-C in all cases when compared with M-o-M**.** Round corner geometry of 4 mm showed a better reduction in contact stress for larger radial clearance as well as for increased lateral head displacements for both M-o-M and C-o-C. For M-o-M pair, 2 and 4 mm round corner geometries are highly preferable for larger radial clearances to avoid edge loading. Similarly for C-o-C pairs 4 mm arc radius is found to be better in reducing the contact stress and compressive stress if larger radial clearances are preferred. The study also showed that even if lateral head displacements are larger, for smaller radial clearances, round corner geometry showed a greater reduction in contact and yield stress values for M-o-M. Thus it is evident from the present study, fracture and stripe wear occurring in ceramic pairs could be minimised to a greater extent if round corner geometries are preferred.



(a) Contact pressure (b) von-Mises stress

Figure 7. Comparison of current study with existing study.

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