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Research article

Selection of Materials and Manufacturing Processes for Total Hip Arthroplasty Components

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A B S T R A C T

This study assessed material and process options for the femoral component, femoral head, and acetabular liner, excluding the outer acetabular cup. Materials were screened for biocompatibility, chemical and corrosion resistance, and load-bearing capacity, then compared using component-specific criteria. CES Selector (CES EduPack 2013) screened shaping and finishing processes. Outputs were checked against material-specific processing constraints, and relative unit-cost trends were examined by batch size. Ti-6Al-4V was selected for femoral component process analysis, while Co-Cr-Mo was retained as an alternative. Forging had a lower relative unit-cost index than HIP. For the femoral head, Al_2O_3 and ZrO_2 were retained for process analysis. BIOLOX® Delta was assessed within the technical-ceramic group, and Co-Cr-Mo was retained as a metallic alternative. Pressing and sintering or powder injection molding (PIM), followed by grinding, were identified. UHMWPE was selected for the acetabular liner, and HXLPE was considered a modified variant. Generic screening identified injection molding, which was not directly adopted for medical-grade UHMWPE. The retained routes were compression molding or ram extrusion of semi-finished stock, followed by precision machining. Together, the results support component-specific choices. Experimental validation and production data are needed to confirm feasibility and estimate actual costs.

1. INTRODUCTION

Hip osteoarthritis (coxarthrosis) may cause chronic pain, stiffness and restricted mobility, thereby limiting the ability to perform activities of daily living. When symptoms substantially impair physical function, treatment may involve total hip arthroplasty. In a longitudinal study of patients undergoing total hip or knee replacement, G. A. Mezey et al. reported significant postoperative improvements in quality of life. Patients with hip osteoarthritis showed the greatest gains in the WOMAC pain, stiffness and physical function domains compared with patients with knee osteoarthritis [1].

Total hip arthroplasty replaces damaged joint surfaces with prosthetic components. The femoral stem is implanted in the femur and coupled to the femoral head, while the acetabular liner provides the bearing surface against the head and permits movement at the joint (Fig. 1).

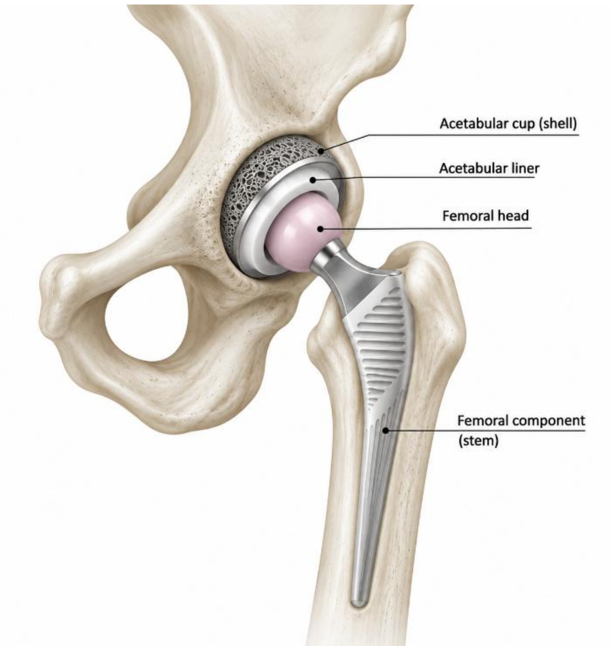


Fig. 1. Main components of a total hip prosthesis: femoral component, femoral head, acetabular liner, and acetabular cup. Source: Authors' own illustration based on the literature synthesis (2026).

Long-term implant performance depends on the behavior of each component and on the interactions between them. The clinical relevance of these interactions is reflected in the Bayesian network meta-analysis by R. Merfort et al., which compared different material combinations of femoral heads and acetabular liners and found differences in wear and revision outcome [2].

The natural hip is a ball-and-socket joint formed by the femoral head and the concave articular surface of the acetabulum. During weight-bearing and locomotion, the forces acting on the joint reflect the combined effects of body weight, muscle forces and ground-reaction forces. Hip loading is therefore dynamic and cannot be described solely in terms of static body weight. In a model integrating gait data, musculoskeletal analysis and finite element analysis, B. Xiong et al. found that hip-joint reaction forces and contact stresses varied throughout the gait cycle, with muscle forces included in the analysis [3]. A scoping review of in vivo and cadaveric studies by P. Dantas et al. likewise highlighted that hip contact pressures vary with loading conditions and joint morphology [4].

The biomechanical conditions described above determine the requirements for the implant components. The femoral stem transfers loads from the femoral head and neck to the femur. Because the resultant force acts eccentrically relative to the femoral component's longitudinal axis, the femoral component is subjected to combined axial loading, bending and torsion. In addition to strength and fatigue resistance, the material's elastic modulus is therefore important because it affects load transfer between the femoral component and the bone. R. Burchard et al. showed that reducing femoral component stiffness can mitigate stress shielding, while the magnitude of this effect also depends on femoral component design [5]. Material selection must therefore be considered in relation to implant geometry and loading conditions.

The femoral head and acetabular liner serve a different function. Together, they form the bearing couple and are exposed to repeated contact, friction and wear. The head material should therefore be assessed not only in terms of hardness and strength, but also by its tribological performance in combination with the liner and the surface quality and geometric accuracy achievable in manufacture. In a Bayesian network meta-analysis of clinical studies, R. Merfort et al. reported the lowest wear penetration for the Al_2O_3–Al_2O_3 couple, while a ZrO_2 head combined with an HXLPE liner had the lowest revision rate [2]. These findings highlight the importance of evaluating the bearing couple as a material combination. For acetabular liners, F. Migliorini et al. found that XLPE and HXLPE were associated with the lowest wear penetration and revision rates among the polyethylene formulations compared, at approximately seven years of follow-up [6].

Material properties are only one part of the selection process. The femoral component geometry, the spherical surface of the femoral head, the taper junction between the stem and head, and the inner surface of the acetabular liner each impose distinct requirements on primary shaping, machining and final surface quality. A manufacturing process must be compatible with both the material and the geometry while meeting the required functional tolerances and surface roughness. Recent studies have examined the mechanical response of femoral components made from different materials, femoral implant design in the context of forging, and the processability of UHMWPE and UHMWPE-based blends [7-10].

These requirements call for materials and manufacturing processes to be selected according to the function of each component, rather than as a single choice for the entire prosthesis. Accordingly, materials and manufacturing processes for the femoral component, femoral head and acetabular liner are assessed using component-specific criteria. Primary shaping and finishing are considered separately, alongside the relative unit-cost index as a function of production batch size. The outer acetabular cup is excluded from the analysis.

2. MATERIALS AND METHODS

The analysis covered the femoral component, femoral head, and acetabular liner. The acetabular cup is shown to illustrate the complete prosthesis assembly (Fig. 1), but it was excluded from the material comparison and manufacturing-process analysis.

Each component was analysed separately using the same sequence of steps. First, exclusion criteria and material-comparison criteria were defined. Material variants that met the initial requirements were then assessed according to properties relevant to the function of each component. The initial screening criteria included biocompatibility, chemical and corrosion resistance in the physiological environment, and the ability to withstand characteristic loads. Materials were not assigned a single composite numerical score. The overall workflow, from defining component requirements to selecting material–process routes, is summarised in Fig. 2.

Manufacturing processes for the material variants retained for further analysis were initially screened using CES Selector from the CES EduPack 2013 software package (https://ansys.synopsys.com/products/materials/granta-edupack). The Process Universe: Edu Level 2 Shaping database was used for the femoral component and femoral head, while the Process Universe: Edu Level 3 Shaping Processes database was used for the acetabular liner. Primary shaping and finishing processes were assessed separately.

Process screening was based on material group, geometry, mass, characteristic section thickness, required tolerance, surface roughness, and planned production volume. The processes identified by the software were then reviewed in light of the processing characteristics of the materials and the requirements of the functional surfaces.

The economic comparison examined changes in the relative unit-cost index as a function of production-batch size, with common model input parameters held constant. The index was used to compare the relative economic performance of the processes and does not represent absolute manufacturing costs.

3.1 Femoral component

The femoral component transmits joint loads to the femur and is subjected to repeat mechanical loading. Consequently, strength and fatigue resistance are key material requirements. Corrosion resistance and biocompatibility must also be considered for long-term implantation in the physiological environment [11,12].

The femoral component has a complex three-dimensional geometry, with the shape and dimensions of its cross-section varying along the longitudinal axis (Fig.3). Its proximal and distal regions, neck, and taper junction with the femoral head have distinct geometric and functional requirements [13].

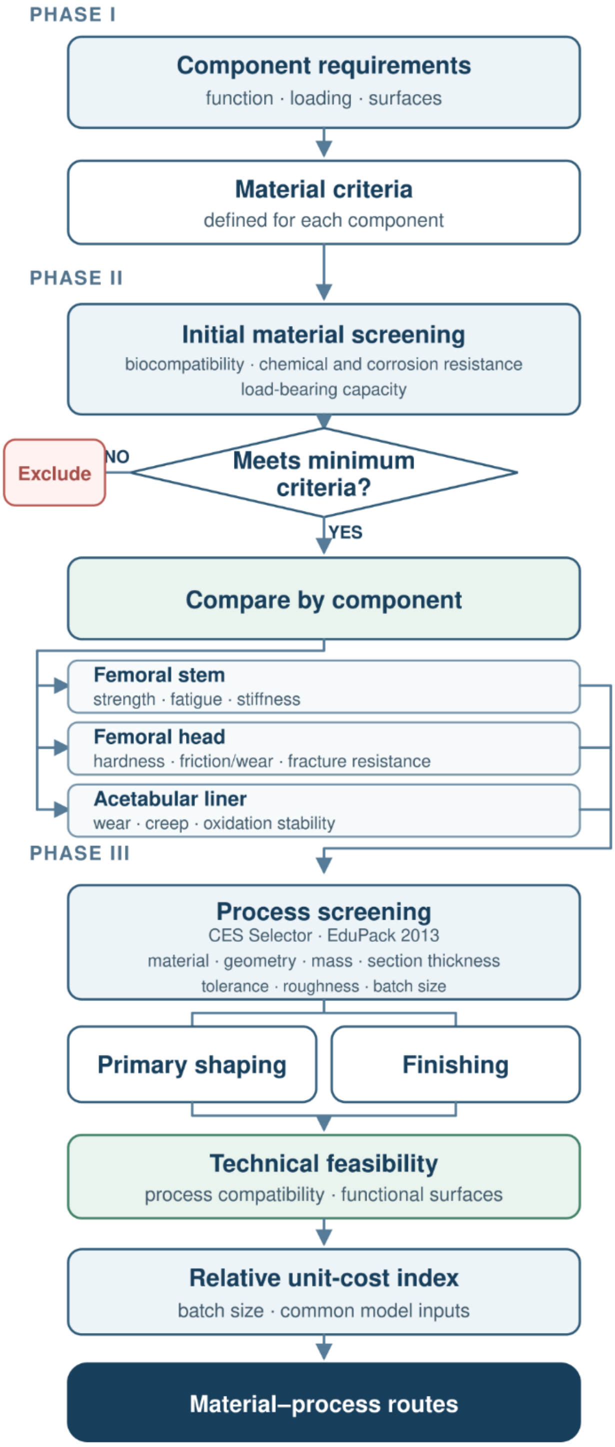


Fig. 2. Component-specific workflow for selecting materials and manufacturing processes for the femoral component, femoral head, and acetabular liner. Source: Authors' own illustration based on the literature synthesis (2026).

These features informed the femoral component's classification for manufacturing process selection, the determination of characteristic section thickness, and the identification of surfaces requiring separate finishing operations.

The fixation method also determines the surface requirements of the femoral component. In cemented fixation, primary stability is achieved through bone cement, whereas in cementless fixation, surface topography and porosity affect initial mechanical stability and bone ingrowth [11,14].

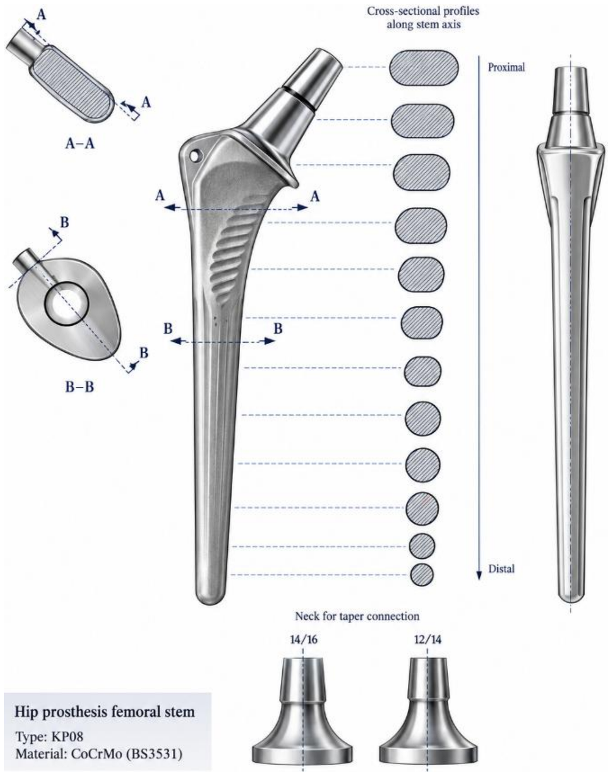


Fig. 3. Geometric features of the femoral component: representative cross-sections along the longitudinal axis, proximal and distal regions, and the taper junction with the femoral head [13]. Source: Authors' own illustration based on the literature synthesis (2026).

The elastic modulus was also considered because it affects load transfer between the implant and the femur. A closer stiffness match between the implant and bone may help mitigate stress shielding, although the effect also depends on stem design [5].

Three metallic materials were selected for comparison: Ti-6Al-4V titanium alloy, Co-Cr-Mo alloy, and 316L austenitic stainless steel. The implant-grade forms of these materials are specified in the relevant literature and standards [7,15-18].

Material-selection criteria and their functional relevance for the femoral component were established (Table 1). Primary shaping and finishing processes were screened separately. For the software analysis, the femoral component was classified as a solid three-dimensional geometry with variable cross-sections. Primary shaping was screened by material group, geometry, mass, characteristic section thickness, and planned production volume. Finishing was additionally screened by dimensional tolerance and surface roughness (Table 2) [19-21].

Table 1. Material-selection criteria for the femoral component [5,7,11,12].

Criterion	Functional significance
Mechanical strength	Resistance to permanent deformation and fracture under combined axial, bending, and torsional loading
Fatigue resistance	Maintenance of mechanical integrity under prolonged cyclic loading
Elastic modulus	Effect on load transfer between the implant and bone, and on mitigating stress shielding
Density	Effect on implant mass
Corrosion resistance	Long-term material stability in the physiological environment
Biocompatibility	Safe long-term contact with tissues and body fluids
Surface properties	Ability to achieve appropriate initial stability, biological fixation, and osseointegration
Manufacturing properties	Suitability for primary shaping, machining, finishing, and subsequent surface modification

Table 2. Input parameters for the selection of manufacturing processes for the femoral component.

Parameter	Requirement
Material group	Metals; the specific material group was determined by the results of the material-screening stage
Geometry	Complex solid three-dimensional geometry with variable cross-sections
Mass	0.20–0.50 kg
Characteristic section thickness	5–20 mm
General dimensional tolerance	< 0.10 mm
Critical surfaces	Tolerance < 0.02 mm
Roughness of finished surfaces	R_a=1.5–2.5 μm for the surfaces included in CES screening; stricter requirements were considered separately for critical surfaces
Production volume	10,000–100,000 units per year
Additional technological requirement	Suitability for appropriate finishing and surface-treatment processes

The stem–head taper and other critical surfaces were assessed against the tighter dimensional-tolerance requirement (<0.02 mm) and the capabilities of precision-finishing processes.

3.2 Femoral head

The femoral head transfers load from the articulation to the femoral component. Its spherical outer surface articulates with the acetabular liner, where friction and wear occur. Their extent depends on contact loading, the material combination, geometric accuracy, surface condition, and lubrication [5].

The femoral head comprises a spherical articulating surface and an internal conical bore that mates with the stem taper. The spherical surface requires high sphericity and low roughness, while the taper interface requires dimensional accuracy and mechanical stability. The component geometry is shown in Fig. 4.

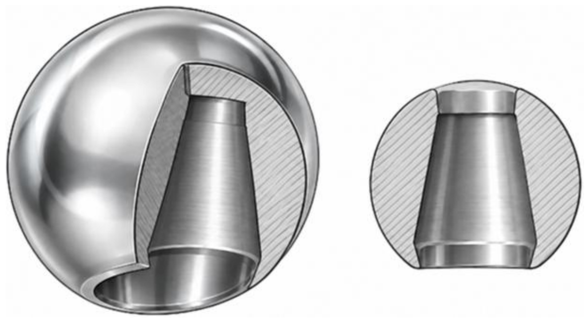


Fig. 4. Femoral head [22]. Source: Authors' own illustration based on the literature synthesis (2026).

Material selection for the femoral head encompassed monolithic oxide ceramics, represented by Al_2O_3 and ZrO_2, the zirconia-reinforced alumina composite BIOLOX® Delta, and the metallic alloys Co-Cr-Mo and Ti-6Al-4V. Including these material classes enabled their assessment under the same component-specific criteria, which covered mechanical strength, hardness, resistance to wear and fracture, and the ability to achieve the required finish of the articulating surface (Table 3). The relevant implant-grade materials are specified in the applicable ISO standards [14-18].

Ti-6Al-4V was included to assess its suitability against the same criteria as the other materials. The wear resistance of its uncoated surface was considered a potential limitation, but not a predetermined reason for exclusion. Friction and wear were evaluated in relation to the material combination and contact conditions of the articulating pair, rather than as properties of an individual material alone [19-21].

Table 3. Material-selection criteria for the femoral head.

Criterion	Functional significance
Mechanical strength	Ability to withstand contact loading without permanent deformation or fracture
Hardness	Resistance to scratching, microabrasion, and localized damage to the articulating surface
Wear resistance	Preservation of contact-surface geometry and reduction in wear-particle generation
Tribological performance of the bearing couple	Reduction of friction, resistance to relative motion, and wear during contact with the acetabular liner
Fracture toughness	Resistance to crack initiation and propagation, particularly in ceramic materials
Chemical and phase stability	Preservation of material structure and properties during long-term exposure to the physiological environment
Biocompatibility	Safe long-term contact with tissues and body fluids
Finishing capability	Ability to achieve the required sphericity, dimensional accuracy, and very low roughness of the articulating surface

Table 4. Input parameters for selecting manufacturing processes for the ceramic femoral head.

Parameter	Requirement
Material group	Technical ceramics: Al_2O_3 and ZrO_2
Geometry	Solid 3D, circular geometry with a spherical functional surface
Diameter	22–36 mm
Mass	0.03–0.05 kg
Characteristic section thickness	2–8 mm
Dimensional tolerance	<0.02 mm
Articulating-surface roughness	Ra < 0.05 µm
Production volume	10,000–100,000 units per year
Additional technological requirement	High sphericity and suitability for precision finishing

Process screening for the ceramic femoral head used the Process Universe: Edu Level 2 Shaping database. Al_2O_3 and ZrO_2 were included; because BIOLOX® Delta was not available as a separate entry, it was represented by the technical-ceramics group, with its specific properties considered separately. The head was classified as a Solid 3D, Circular component. Primary shaping was screened by material group, geometry, mass, characteristic section thickness, and production volume. Finishing was additionally screened for dimensional tolerance, sphericity, and articulating-surface roughness (Table 4) [19-21].

Ceramic-specific process considerations included dimensional changes during thermal processing and the potential for surface and subsurface damage during precision finishing.

3.3 Acetabular liner

The inner spherical surface of the acetabular liner articulates with the femoral head. The liner bears and distributes contact loads while allowing relative motion within the joint. Its performance is therefore associated with friction, wear, wear-particle generation, and dimensional stability [5].

The inner surface must match the geometry of the femoral head and meet the required sphericity and surface-roughness specifications. The outer surface enables the liner to seat and remain securely within the acetabular shell. In this study, acetabular liner refers to the articulating component (Fig. 5). The outer shell, which is fixed in the pelvis, was excluded from the analysis [19-21].

Fig. 5. Acetabular liner [23].

The material comparison covered polymeric, ceramic, and metallic bearing surfaces: UHMWPE, including HXLPE as its cross-linked variant; the oxide ceramics Al_2O_3 and ZrO_2; and Co-Cr-Mo alloy. The implant-grade UHMWPE powder and moulded forms are specified in the applicable standards [24,25]. The criteria used to compare these materials are summarized in Table 5 [19-21].

Table 5. Material-selection criteria for the acetabular liner.

Criterion	Functional significance
Tribological performance of the bearing couple	Minimizing friction and resistance to relative motion at the interface with the femoral head
Wear resistance	Maintaining the geometry of the articulating surface and reducing wear-particle generation
Fatigue resistance	Maintaining integrity under long-term cyclic contact loading
Fracture toughness and impact resistance	Preventing crack initiation and propagation, and localized damage under sudden changes in loading
Creep resistance	Maintaining dimensions, geometric conformity, and contact conditions under prolonged loading, particularly in polymeric materials
Chemical and oxidative stability	Preserving material structure and properties during manufacturing, sterilization, storage, and long-term service in the physiological environment
Biocompatibility	Ensuring safe long-term contact with tissues and body fluids
Finishing capability	Achieving the required sphericity, dimensional accuracy, and surface roughness of the articulating surface
Manufacturing properties	Enabling repeatable and economically viable production at the planned volume

For HXLPE, the assessment considered how cross-linking and subsequent thermal stabilization may affect wear, oxidation resistance, and mechanical properties. Friction and wear were evaluated in relation to the specific head–liner combination, contact loading, surface condition, and lubrication, rather than as properties of the liner material alone [19-21].

Process screening for the acetabular liner was performed for UHMWPE using the Process Universe: Edu Level 3 Shaping Processes database. HXLPE was not treated as a separate material group because it is a cross-linked and subsequently stabilized form of UHMWPE; the liner's base geometry is formed before cross-linking. The liner was classified as a Solid 3D, Circular component. This classification represented its overall geometry, while the inner spherical surface and outer shell-fitting geometry were assessed as functional surfaces with distinct requirements. Primary shaping was screened by material group, geometry, mass, characteristic section thickness, and production volume; finishing was additionally screened for dimensional tolerance, sphericity, and surface roughness (Table 6) [19-21].

Table 6. Input parameters for selecting manufacturing processes for the UHMWPE acetabular liner.

Parameter	Requirement
Material	UHMWPE
Geometry	Solid 3D, circular geometry with an internal spherical functional surface
Outer diameter	40–66 mm
Mass	0.05–0.08 kg
Characteristic section thickness	6–8 mm
Dimensional tolerance	<0.02 mm
Articulating-surface roughness	Ra < 0.05 μm
Production volume	10,000–50,000 units per year
Additional technological requirement	High sphericity, dimensional stability, and appropriate articulating-surface quality

For UHMWPE, the process-route assessments considered direct compression moulding or ram extrusion of semi-finished stock, followed by precision machining of the functional surfaces. Cross-linking, thermal stabilization, and sterilization were treated as subsequent operations and considered in assessing the overall process route.

3. RESULTS

The initial exclusion screening for the femoral component was passed by Ti-6Al-4V, Co-Cr-Mo, and 316L stainless steel. Their properties and the outcomes of the subsequent comparison are summarized in Table 7.

Ti-6Al-4V was selected for further process analysis, while Co-Cr-Mo was retained as a technically feasible alternative. Forging and hot isostatic pressing (HIP) were identified as primary shaping processes for Ti-6Al-4V. Both covered the analysed production volume of 10,000–100,000 units per year, while the software output indicated a broader economically viable batch-size range for forging (Fig. 6).

Table 7. Outcomes of material screening for the femoral component.

Material	Comparative results	Screening outcome
Ti-6Al-4V	Elastic modulus of approximately 110 GPa; density of approximately 4.5 g/cm^3; high fatigue and corrosion resistance; potential for forming surfaces that support osseointegration	Retained for process analysis
Co-Cr-Mo	High mechanical strength and fatigue resistance; elastic modulus of approximately 220 GPa; density of approximately 8.3 g/cm^3; difficult to machine	Retained as a technically feasible alternative
316L	Adequate strength and good machinability; elastic modulus of approximately 190–200 GPa; lower fatigue and corrosion resistance than Ti-6Al-4V and Co-Cr-Mo	Not retained for further process analysis

The relative unit-cost index decreased with increasing batch size for both forging and HIP, then entered a range of slower change at larger production volumes. Forging had a lower relative index throughout the analysed range (Fig.7).

Screening of finishing processes against tolerance, surface roughness, and production volume identified milling, turning, grinding, abrasive jet machining, and electrical discharge machining (Fig.8).

Milling, turning, and grinding covered the specified tolerance and roughness requirements. Of these, only grinding also covered the stricter requirements for critical surfaces (Fig.9).

Screening of surface-treatment processes against corrosion-protection, hardness, and surface-texture requirements identified anodizing and thermal spraying of metal powder (Fig.10).

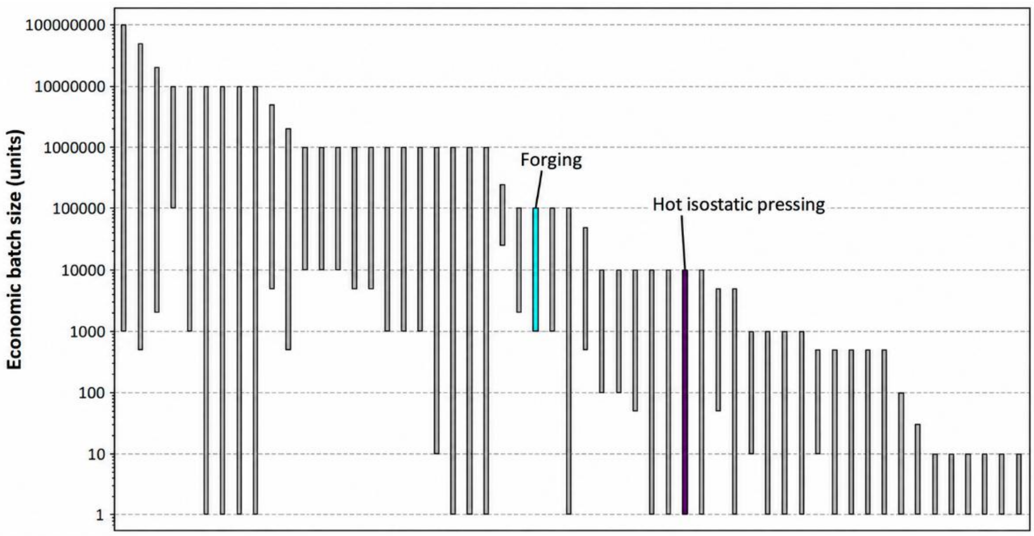
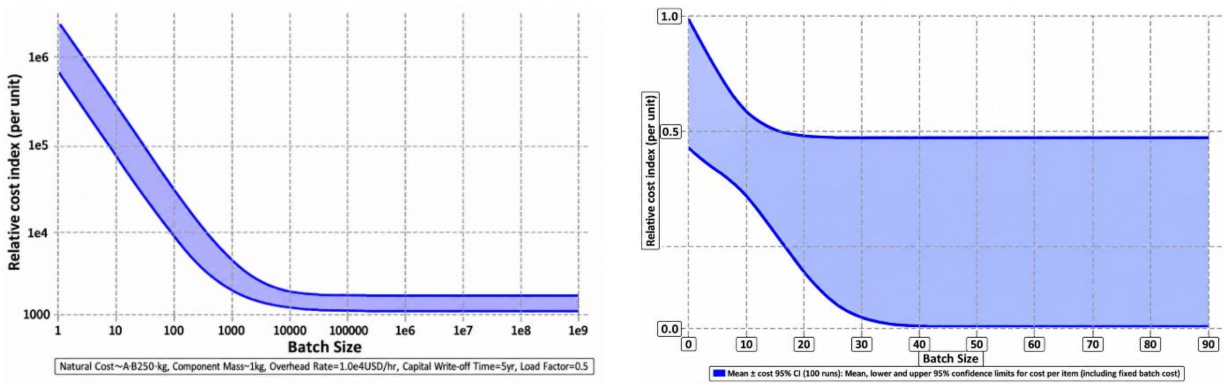


Fig. 6. Results of screening primary shaping processes for the femoral component.



(a) (b)

Fig. 7. Relative unit-cost index for the femoral component as a function of batch size: (a) Forging, (b) Hot isostatic pressing (HIP).

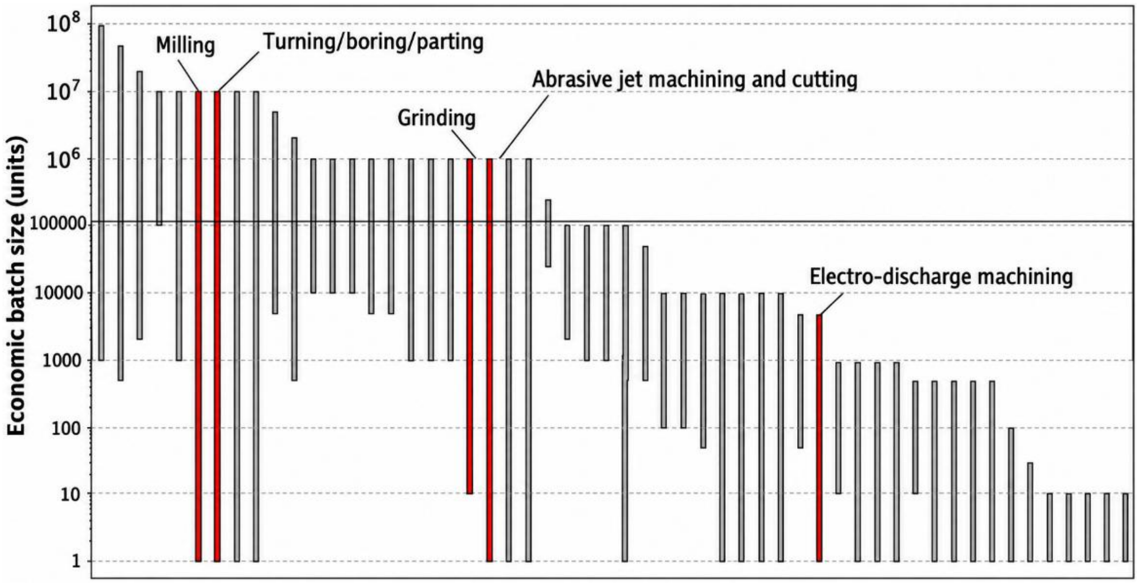


Fig. 8. Finishing processes for the femoral component identified by screening according to economic batch-size range.

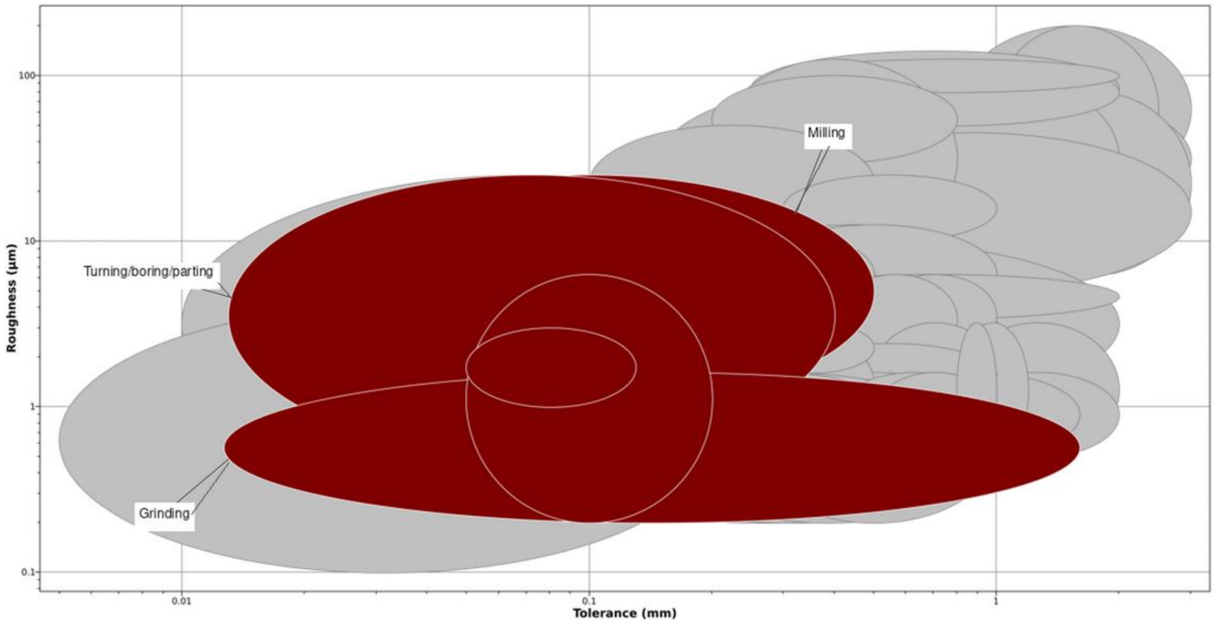


Fig. 9. Achievable tolerance and surface roughness of the selected finishing processes for the femoral component.

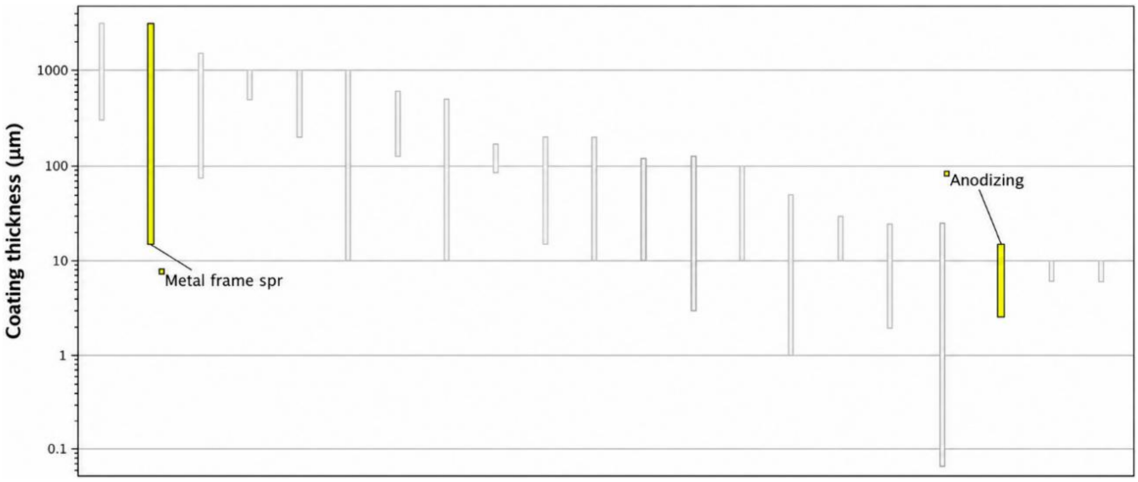


Fig. 10. Results of screening surface-treatment processes for the femoral component.

The comparative assessment showed that Al_2O_3 and BIOLOX® Delta had the highest hardness values among the materials considered, while ZrO_2 had greater fracture toughness than monolithic Al_2O_3. Co-Cr-Mo was retained as a metallic alternative. Ti-6Al-4V was not retained for the articulating surface because of the limited wear resistance of its uncoated surface. The results are summarized in Table 8.

For further process analysis, Al_2O_3 and ZrO_2 were represented by separate material records in the database. BIOLOX® Delta was assessed within the technical-ceramics group because it was not available as a separate entry. Co-Cr-Mo remained a metallic alternative; the process results below apply to the ceramic femoral head.

Pressing and sintering and powder injection molding (PIM) were identified as primary shaping processes. Both covered the analyzed production volume of 10,000–100,000 units per year, while PIM extended to a larger upper batch-size range in the software output (Fig. 11). The relative unit-cost index decreased with increasing batch size for both processes, then approached approximately constant values of the same order at the upper end of the analyzed range (Fig. 12).

Grinding was identified as the finishing process whose applicability range covered the specified dimensional tolerance of <0.02 mm and articulating-surface roughness of <0.05 µm (Fig. 13). The resulting process route therefore comprises pressing and sintering or PIM, followed by grinding.

Table 8. Outcomes of material screening for the femoral head.

Material	Comparative results	Screening outcome
Al_2O_3	Hardness of 1960–2300 HV; elastic modulus of approximately 380 GPa; high wear resistance; lower fracture toughness	Retained
ZrO_2	Hardness of approximately 1200 HV; elastic modulus of approximately 210 GPa; fracture toughness of approximately 9–10.5 MPa·$m^{1/2}$	Retained
Co-Cr-Mo	High strength and suitability for precision finishing; lower hardness than the ceramics considered	Retained as a metallic alternative
Ti-6Al-4V	Low density and elastic modulus of approximately 110 GPa; insufficient wear resistance of the uncoated surface	Not retained for the articulating surface
BIOLOX® Delta	Hardness of approximately 2000 HV; high wear resistance and greater resistance to crack initiation and propagation than monolithic Al_2O_3	Retained

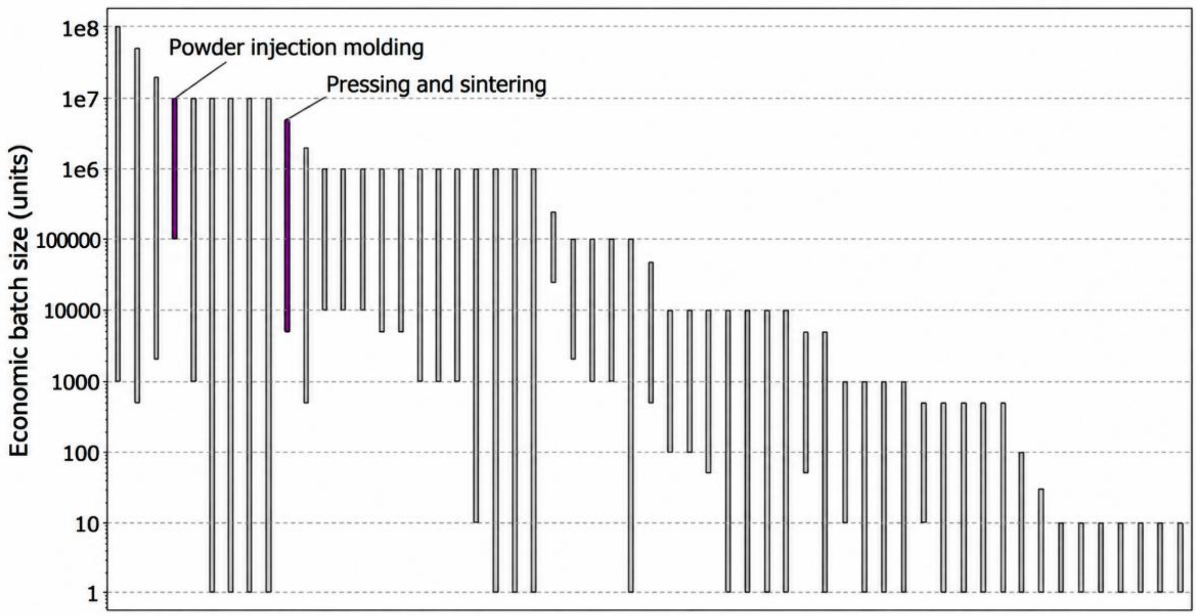
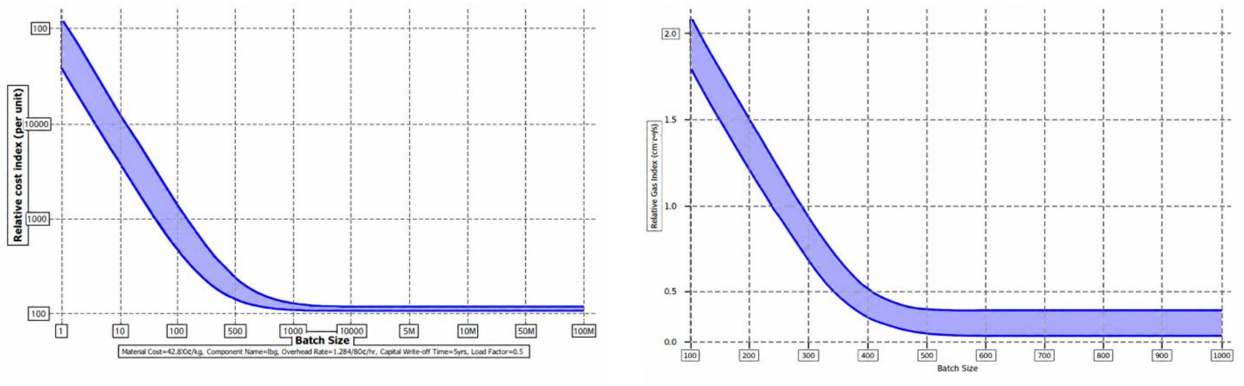


Fig. 11. Results of screening primary shaping processes for the ceramic femoral head.



(a) (b)

Fig. 12. Relative unit-cost index for the ceramic femoral head as a function of batch size; a) pressing and sintering, b) powder injection moulding (PIM).

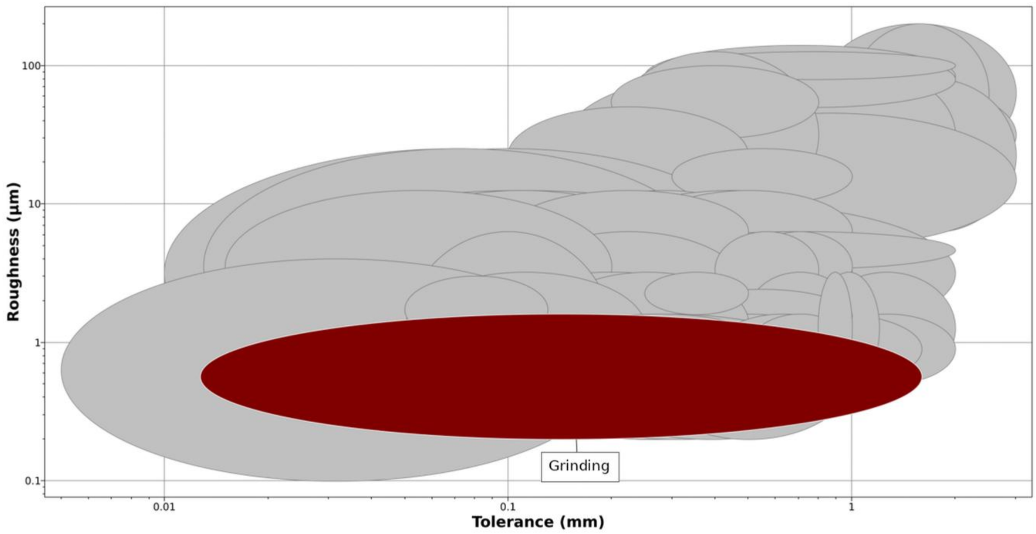


Fig. 13. Results of screening finishing processes for the ceramic femoral head against tolerance and surface-roughness requirements.

Table 9. Outcomes of material screening for the acetabular liner.

Material	Comparative results	Screening outcome
UHMWPE	Tensile strength of approximately 40 MPa; elongation of 200–300%; low coefficient of friction; susceptible to wear, creep, and oxidation	Retained for process analysis
HXLPE	Lower wear than conventional UHMWPE; properties depend on the cross-linking and thermal-stabilization processes	Retained as a modified UHMWPE variant
Al_2O_3 / ZrO_2	High hardness and wear resistance; greater stiffness and susceptibility to fracture than polymeric alternatives	Retained as ceramic alternatives
Co-Cr-Mo	High strength and wear resistance; metallic articulating surface	Retained as a metallic alternative

Further process analysis was conducted for the UHMWPE acetabular liner. HXLPE was not treated as a separate material group in the process database because the liner's base geometry is formed from UHMWPE; while cross-linking and thermal stabilization are carried out in subsequent manufacturing stages.

Based on the material, geometric, and manufacturing constraints, the generic CES Selector database identified thermoplastic injection molding as a primary shaping process (Fig.14). Subsequent assessment showed that this result could not be directly applied to medical-grade UHMWPE. The process routes retained as technically applicable were direct compression molding or ram extrusion of semi-finished stock, followed by precision machining of the functional surfaces.

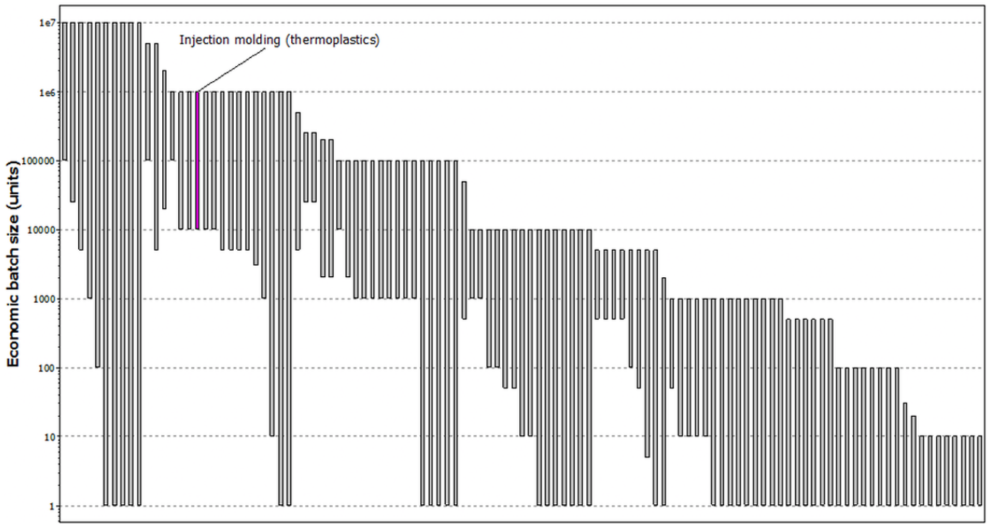


Fig. 14. Software-screening result for the primary shaping process for the UHMWPE acetabular liner.

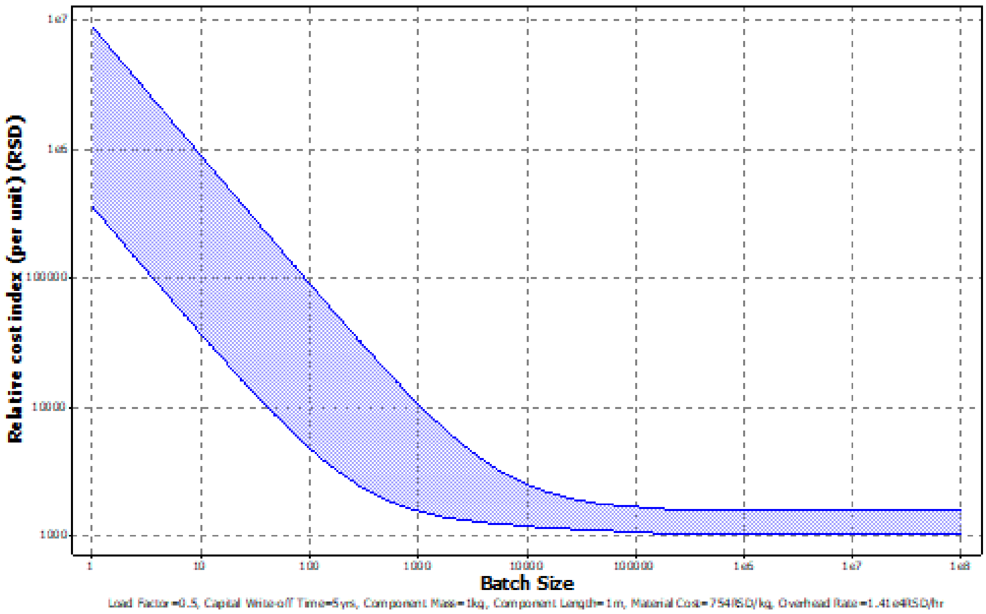


Fig. 15. Relative unit-cost index of generic thermoplastic injection molding as a function of production batch size.

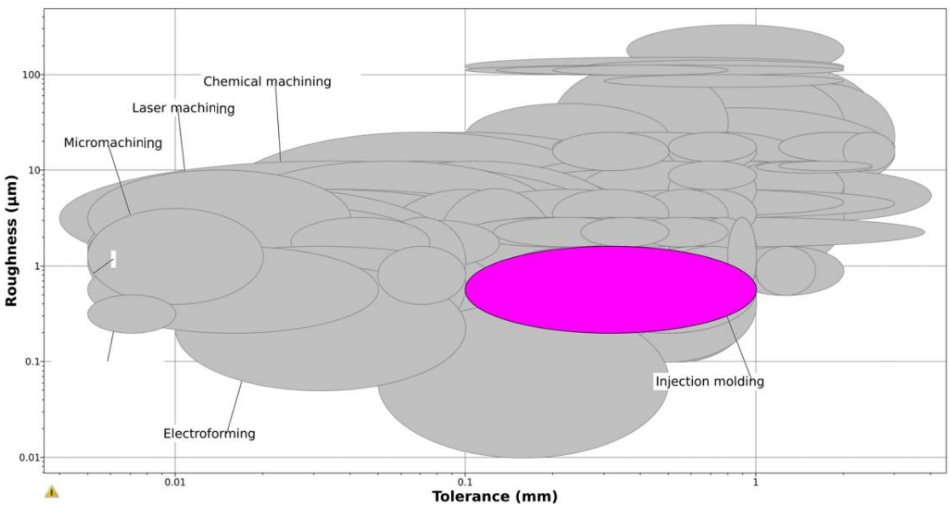


Fig. 16. Results of process screening against the tolerance and surface-roughness requirements for the acetabular liner.

For thermoplastic injection molding, the process identified by the generic database, the relative unit-cost index decreased as batch size increased and then approached an approximately constant value (Fig. 15). This result applies only to the generic injection-molding model; it does not compare the process routes retained after assessing their compatibility with medical-grade UHMWPE.

Screening against the tolerance and surface-roughness requirements identified several processes, including micromachining, laser machining, chemical machining, and thermoplastic injection molding (Fig. 16). After assessing their compatibility with UHMWPE and the requirements of the inner spherical articulating surface, precision machining of semi-finished stock was retained for producing the final geometry.

Table 10. Summary of material and manufacturing routes identified for the analysed components.

Component	Material taken forward for process analysis / alternatives	Primary shaping	Finishing and subsequent treatment
Femoral stem	Ti-6Al-4V; Co-Cr-Mo retained as a material alternative	Forging; HIP as an alternative process	Milling, turning or grinding; anodizing or thermal spraying of metal powder, depending on surface function
Femoral head	Al_2O_3 and ZrO_2; BIOLOX® Delta considered within the technical-ceramics group; Co-Cr-Mo retained as a metallic alternative	Pressing and sintering or powder injection molding (PIM)	Grinding and final polishing of the articulating surface
Acetabular liner	UHMWPE; HXLPE as a cross-linked and thermally stabilized variant	Direct compression molding or ram extrusion of semi-finished stock	Precision machining; subsequent cross-linking and thermal stabilization for HXLPE

The resulting manufacturing route for the polymeric acetabular liner comprises compression molding or ram extrusion of UHMWPE semi-finished stock, followed by precision machining of the inner spherical articulating surface and outer joining geometry. For HXLPE, cross-linking and thermal stabilization are additional subsequent stage.

The component-specific screening identified the material variants and manufacturing routes summarized in Table 10. The table distinguishes the materials taken forward for process analysis from alternatives retained during material evaluation, and reports the corresponding shaping and finishing stages.

4. DISCUSSION

The results indicate that the selection of materials and manufacturing processes for total hip arthroplasty depends on the function of each component. The femoral component primarily transfers load to the femur, whereas the femoral head and acetabular liner form an articulating pair subject to friction and wear. Accordingly, the findings do not identify a single material as suitable for every component. Instead, they define material and manufacturing options in relation to the requirements of each component. This approach allows mechanical, tribological, and manufacturing properties to be considered together, alongside separate assessments of finishing processes and relative unit-cost trends.

For the femoral component, Ti-6Al-4V was selected for further process analysis because of its favourable combination of low density, a lower elastic modulus, fatigue and corrosion resistance, and potential for surface modification. Co-Cr-Mo was retained as a technically viable alternative, whereas 316L was not carried forward to the next stage under the adopted criteria. This outcome is consistent with the numerical analysis of femoral components by D. M. Anticona-Valderrama et al. In their comparison of Ti-6Al-4V, CoCr, and AISI 316L, Ti-6Al-4V showed greater predicted fatigue resistance, a longer service life, and lower stress levels under static and transient loading [7]. The comparison with D.M. Anticona-Valderrama et al. is limited by the scope of their model, which examined specific femoral component geometry under defined loading conditions. The present study considered a wider range of mechanical, biological, and manufacturing requirements. The exclusion of 316L therefore reflects the criteria applied here. It does not establish that the alloy is generally unsuitable for femoral component.

Elastic modulus was included among the evaluation criteria because it affects load transfer between the implant and the femur. In a numerical study, R. Burchard et al. found that reducing femoral component stiffness alleviated stress shielding, although the effect also depended on femoral component design. In their model, the most favourable load transfer was achieved with a short, anatomically shaped stem of reduced stiffness [5]. These findings support including stiffness in material assessment, while showing that biomechanical performance cannot be inferred from elastic modulus alone. Because the present study did not include a numerical simulation of the implant–bone system, selecting Ti-6Al-4V does not by itself demonstrate a reduction in stress shielding.

For primary shaping of the femoral component, CES screening identified forging and hot isostatic pressing (HIP) as processes that cover the analysed production volume. Forging showed a lower relative unit-cost index and a wider range of economically viable batch sizes. V. Tuninetti et al. examined the shape optimization of a Ti-6Al-4V femoral component to support more efficient forging. Their analysis of stress, deformation, and load transfer provides relevant manufacturing context, but does not directly compare the cost of forging and HIP [8]. The economic advantage observed here should therefore be understood as a result of the software model, rather than as evidence of lower actual production costs. The finishing results further show that primary shaping alone does not determine the final component quality: milling, turning, and grinding met the general tolerance and surface-roughness requirements, but only grinding also covered the stricter requirements for critical surfaces. This is particularly relevant to the taper junction with the femoral head, where dimensional accuracy and surface condition affect the fit. Anodizing and thermal spraying of metal powder were also identified for further consideration where the function of a particular surface warrants modification; their use therefore depends on the requirements of that surface.

For the femoral head, technical ceramics offered a favourable combination of hardness, wear resistance, and the potential to achieve a high-quality articulating surface. The comparison also revealed differences within this group: Al_2O_3 and BIOLOX® Delta showed high hardness, whereas ZrO_2 had greater fracture toughness than monolithic Al_2O_3. Co-Cr-Mo was retained as a metallic alternative, while Ti-6Al-4V did not meet the applied wear-resistance criteria for an uncoated articulating surface. These results should be considered in the context of the bearing couple. In a Bayesian network meta-analysis of 663,038 hip arthroplasties, R. Merfort et al. reported the lowest wear for the Al_2O_3–Al_2O_3 bearing couple and the lowest revision rate for a ZrO_2 head paired with an HXLPE liner. Their findings underline that tribological performance depends on the material combination, rather than on the hardness or wear resistance of either component alone. However, the clinical meta-analysis does not establish a ranking based on individual mechanical properties, nor can its findings be attributed to a specific commercial ceramic without direct comparative evidence [2].

For the ceramic femoral head, both pressing and sintering and powder injection molding (PIM) covered the planned production volume. In the CES model, PIM extended to a higher upper batch-size limit, while the relative unit-cost indices for the two processes were of a similar order of magnitude. Grinding was the only process whose applicability range covered the specified tolerance and surface-roughness requirements. Final polishing remains an additional requirement for the articulating surface, although it was not identified as a separate outcome of the software screening. The results therefore distinguish between processes identified as technically feasible and the finishing operations needed to achieve the required surface quality.

For the acetabular liner, UHMWPE was taken forward for process analysis, while HXLPE was considered as its subsequently cross-linked and thermally stabilized variant. In a meta-analysis of 60 clinical studies involving 37,352 hip arthroplasties, F. Migliorini et al. associated XLPE and HXLPE with lower wear and revision rates over approximately seven years of follow-up. The authors also noted that the properties of cross-linked polyethylene depend on the degree of cross-linking and subsequent thermal treatment, which may affect its mechanical characteristics [6]. These findings support considering HXLPE for its potential wear advantage, while assessing its performance in relation to the specific modification process used.

A key consideration in the acetabular-liner analysis was whether a process identified by generic CES screening could be applied to the specific UHMWPE variant examined. The database identified thermoplastic injection molding, but this result could not be adopted without further assessment. H. Yang et al. note that UHMWPE's high molecular weight makes conventional processing difficult, and describe compression molding and ram extrusion followed by machining as widely used routes. Their study also examines injection molding of UHMWPE and its blends, however, showing that injection molding should not be ruled out for every formulation [9]. This formulation-specific distinction is further illustrated by D. Sablaniya et al., who produced commercially shaped acetabular liners by injection molding a modified UHMWPE containing short-chain, maleic-anhydride-functionalized polyethylene. Because that material differs from the standard UHMWPE considered in the CES screening, their results do not establish the suitability of injection molding for the material assessed here. Instead, they show that its applicability depends on the formulation, processing conditions, and quality required of the finished liner [10]. Accordingly, compression molding or ram extrusion of semi-finished stock, followed by precision machining, was retained for the UHMWPE considered in this study. For HXLPE, the process route also includes subsequent cross-linking and thermal stabilization.

The economic results should be interpreted within the same limitations. The relative unit-cost indices were calculated using the input parameters defined in the software and allow cost trends to be compared across production batch sizes. For the femoral stem, they provide a comparison of forging and HIP within the CES model. For the acetabular liner, however, the curve represents generic injection molding, which was not adopted as the manufacturing route for the UHMWPE considered here. It therefore does not compare the costs of compression molding and ram extrusion. None of the indices represents an absolute manufacturing cost.

5. CONCLUSION

This study assessed materials and manufacturing routes separately for the femoral component, femoral head, and acetabular liner. Ti-6Al-4V was carried forward for femoral component process analysis, with forging showing a lower relative unit-cost index than HIP. For the ceramic femoral head, pressing and sintering or PIM were identified for primary shaping, followed by grinding; final polishing remains a separate requirement for the articulating surface. For the UHMWPE acetabular liner, compression molding or ram extrusion of semi-finished stock, followed by precision machining, were retained as technically applicable routes. HXLPE additionally requires cross-linking and thermal stabilization. The cost indices provide a relative comparison under the software-defined conditions and do not represent actual manufacturing costs. Further process validation and production-scale cost assessment are needed before these routes can be evaluated for implementation.

Future work should experimentally validate the identified manufacturing routes by assessing dimensional accuracy, surface quality, and mechanical integrity after processing. Tribological testing of specific femoral-head–acetabular-liner combinations and biomechanical analysis of the implant–bone system would help establish how the selected materials and component designs perform under representative conditions. Further economic assessment should use current production data and account for tooling, post-processing, and manufacturing yield, enabling comparison of actual costs across production volumes.

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