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Experimental and finite element analysis of titanium based medial tibial condyle using incremental sheet metal forming

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Incremental Sheet Metal Forming (ISMF) is an innovative manufacturing technique for producing prototypes and manufacturing of complex shaped sheet metal parts. Manufacturing of implants and prosthesis for biomedical applications is a challenging task, because it demands the fabrication of complex intricate structures replicating the shapes of human body parts. An attempt has been made to clearly describe the capabilities and limitations of a new manufacturing technology to fabricate low cost, specific design medical implants. This study aims to fabricate an implant for medial tibial condyle using single point incremental forming and thereby improve the suitability of the single point incremental forming process. This investigation reports the fundamental knowledge on mechanical behavior of titanium grade 2 sheet metal to design and fabrication of knee implants with rigid hemispherical and roller ball forming tools by means of single point incremental forming process. Influence of major process parameters such as forming force, deformation of sheet, sheet thickness and profile accuracy of part have been identified by experimental work and Finite Element (FE) simulations. The result has shown that surface finish of the part formed by the roller ball forming tool is better than hemispherical rigid tool.

Keywords: Incremental sheet metal forming, Knee bone reconstruction, Finite element analysis, Forming tools, Profile accuracy

1 Introduction

In the recent years, there is an increasing demand for the development of innovative manufacturing technologies that are both agile and be able to handle with the industrial process requirements. Incremental Sheet Metal Forming (ISMF) is an innovative approach for producing prototypes and manufacturing of small batch sheet metal parts, where ISMF has been originated with partial hybridization of stretch forming and metal spinning processes. ISMF process can be carried out at room temperature and it requires a Computer Numerical Control (CNC) machining centre with forming tool and a simple fixture support to clamp the sheet. Main characteristics of this technique are its high flexibility, short development time, improved formability of material and cost reduction. Flexibility of the process is mainly related to the fact that Single Point Incremental Forming (SPIF) does not require a dedicated die to form a component compared to other forming processes. This process starts from a flat sheet metal blank, clamped on the fixture which has been mounted on the table of a CNC machine. As a result, the lead time and cost of tooling along with the die cost have been avoided. This technique allows relatively fast and cheap production of small series of sheet metal parts. Elimination of die in this manufacturing process reduces the cost per piece and increases turnaround time for low production run. It has been found that the formability of sheet metal materials under the localized deformation imposed by incremental forming is better than in conventional deep drawing[1].

The biomedical sector has seen a phenomenal growth due to the aid of manufacturing techniques, where medical prosthesis for bone replacement products has enormous market. Bio implants are generally manufactured by deep drawing, grinding, moulding and hydro forming processes. For each of these processes there is a necessity for manufacturing new set of active tools, dies and punch. Recently an emerging forming technique known as incremental sheet metal forming process has been evolved which is capable of forming intricate, asymmetrical components as a result of highly localized deformations. ISMF process forms the component using principle of stretching and bending while maintaining the material's crystal structure. The process can be performed using any type of Computer Numeric Controlled (CNC) milling machine, making it highly available and cost effective to the manufacturing industry. In the medical field, with the help of Computer Tomography (CT), scan images of damaged restorative part details

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have been constructed. The bio-model implants are designed with the help of Computer Aided Design (CAD) software and CNC programme code can be generated by Computer Aided Manufacturing (CAM) software. The custom made bio-models are cost effective when these are modelled by ISMF technique. Also the pre-operative manufacturing is very useful to study and plan the surgery for achieving the expected results. Orthopaedic biomaterials play an important role for manufacturing implants for patients with improved quality and expectancy of life. The biocompatible materials mostly used for biomedical implants are titanium and its alloys[2].

Research work related to the part shape, profile accuracy and dimensional errors, as well as the influence of other process parameters on ISMF process to fabricate bio medical implant has been presented. Vanhove *et al.*[3] have investigated the effectiveness of incremental forming for the production of bio-medical implants using titanium grade 2 sheet for treatment of clavicle fracture with two iterations, where one using a standard spiral tool path on the designed geometry without compensation and other with compensated tool path. Conclusions have been made that by compensating forming tool path, the part could be brought into a satisfactory accuracy range. Formisano *et al.*[4] have discussed the effect of ISMF process parameters on the stress induced during ISMF of conical frusta. Results of finite element analysis are compared with the experimental data and it has been found that finite element model and experimental results are in acceptance level with a maximum discrepancy of 8%. Lu *et al.*[5] has made an attempt to reconstruct cranial plate using single point incremental forming thereby inspecting the efficiency of the process by comparison of experimental testing and Finite Element (FE) simulation. Feature based tool path algorithm have been adopted on TA1 titanium material and fabrication using both conventional ball head and roller ball forming tools have been done. The results has shown that cranial shape can be obtained with satisfactory profile accuracy and surface finish by adopting feature based tool path generation method. Bhoyar *et al.*[6] have elaborated various manufacturing process carried on various biocompatible metallic and non-metallic customized implantable devices. The outcome unveiled a fact that the Ti-6Al-4V alloy which has been used for biomedical implants is not compatible since Vanadium is toxic for human body. Fiorentino *et al.*[7] have discussed the biocompatibility of titanium parts fabricated using incremental forming to provide a justification for the implementation of incremental forming for prosthesis manufacturing. Surface treatments like alkaline and acid anodizing have been done after post fabrication to facilitate the growth of prosthesis substrate layer. Eventually, cellular growth results on the specimens proved the parts to be biocompatible. Hussain *et al.*[8] have studied the stress developed during ISMF process using finite element analysis and has found that ratio of vertical to horizontal stress is a principal factor to control defects in part. Amborgio *et al.*[9] have conveyed an idea of implementing incremental forming process for highly customized medical products manufacturing. The experimental study has been carried out for the manufacturing of ankle support. The influential parameters found during operation are tool size, velocity, tool path generation and lubrication. Outcome has shown that the desired product achieved a discrepancy of 1 mm compared with the designed part. Hussain *et al.*[10] have discussed the effect of tool diameter on the stresses induced during the ISMF process and performed finite element analysis to study the role of tool size with respect to sheet thickness.

Ambrogio *et al.*[11] have adopted super plastic forming and single point incremental forming processes for manufacturing of custom prostheses, instead of subtractive and additive techniques due to time and cost consumption for a single piece production. The mechanical strength of the cranial implants has been assessed by means of impact puncture tests. Impact puncture tests demonstrates that both the adopted manufacturing process did not alter the material characteristics significantly, even though two forming processes produced two implants having different characteristics in terms of thickness distributions and amount of energy absorbed. Ciancio *et al.*[12] have proposed the optimal design of the anchoring system in case of patient specific titanium prostheses by the coupled use of numerical model for structural analysis and statistical techniques. Saidi *et al.*[13] have proposed a reverse engineering approach associated with single point incremental forming process in order to produce titanium prosthesis of human skull. A new incremental forming system based on the use of heat cartridges have been developed to provide a uniform and constant distribution of heat during the warm forming of titanium alloy Ti-6Al-4V skull prosthesis. Honarpisheh *et al.*[14] have investigated electric hot incremental forming process parameters such as wall angle, step size and tool diameter on the response process parameters such as formability, incremental forming force and thickness distribution by experimentally and numerically on the Ti-6Al-4V sheet. The result has shown that the incremental forming force increases with increasing the step size and decreasing the tool diameter. Where the thickness of sheet decreases with increasing the wall angle and decreasing the step size. Hussain *et al.*[15] have investigated the suitable tool and lubricant to form a commercially pure titanium sheet by negative incremental forming process. The surface hardened high speed steel tool and the paste of molybdenum disulphide with petroleum jelly in a specific proportion have produced components with good surface quality.

In the recent years, ISMF has found a lot of applications in the medical specialty sector. There has been an exceptional rise in the requirement for implementation of artificial support structures inside the human body like implants and prosthetic structures. Manufacturing of those structures are often challenging as these parts resemble the complex shape of the human body part of interest. These parts have been manufactured by conventional processes like forming, bending and forging. These processes often require additional tools like punches and dies and would not be value economical once customized structures based on physical body geometry are to be created. Incremental forming would prove price economical with the manufacture of advanced customized structures, because it is a die-less metal forming method capable of manufacturing complex intricate structural parts[16].

The present work discuss a few issues concerning an ISMF process on titanium grade 2 sheet to the design and fabrication of knee implants. The influence of forming force, sheet deformation, profile accuracy and surface finish of hemispherical rigid and roller ball tool while manufacturing knee implants have been studied in detail by Finite Element (FE) simulation and conducting experimental trials. By investigating the process parameters a broad evaluation of the ISMF based knee implant has been constructed.

2 Materials and Methods

2.1 Construction of knee implant model

To assess the quality and performance of incremental forming process, an implant for treatment of posterior tibial condyle replacement was identified for fabrication and finite element analysis. The mechanism causing tibial plateau fractures is complex in high energy injuries, probably coexisting with axial, varus and valgus stresses. In general the treatment involves the fixation of a single laterally based locking plate that holds the fractured funnel like region in the tibial bone as shown in Fig. 1. In severe injury cases, the use of locking plates fails to constrain the fracture region[17]. So implants resembling the shape of the bone need to be fabricated to support the region with increased contact area for better constraint.

The design of a knee implant, which covers the entire funnel shaped fracture region of the tibial bone has to be generated for fabrication and finite element analysis. Titanium grade 2 sheet materials usage in the field of biomedical engineering was identified and mechanical property[18] is listed in the Table 1.

2.2 Generation of part design using 3-d scanners

To facilitate the generation of tool path trajectory for forming tool to fabricate the implant, a CAD model of contour surface that the implant must possess is essential[19]. So the cloud points of tibial bone were obtained using reverse engineering methodology through Advanced Topometric Optical Sensor (ATOS) measuring system. ATOS measuring system is based on optical triangulation and stereo-viewing thus allow

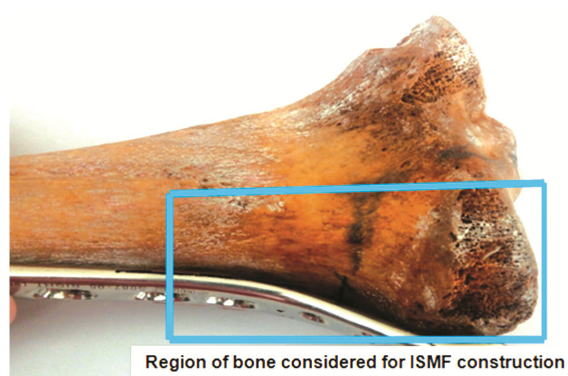

Fig. 1 — Knee bone model taken for ISMF construction.

Table 1 — Mechanical properties of Titanium grade 2 sheets

Yield strength (MPa)	Ultimate strength (MPa)	Young's Modulus (GPa)	Poisson's ratio	Elongation at break (%)	Material density (Kg/m^3)
276	344	103	0.3	20	4500

accurate measurement by capturing shape and size of the visible surface of any three dimensional object. The cloud points obtained through ATOS system were used to generate the CAD model of the bone using CATIA software as shown in Fig. 2.

Using CAD model of the bone, surface representing the fracture prone funnel like region of the bone were extracted using CATIA software to design implants. The designs were developed using CAD softwares, the tool path trajectory for the forming tool to produce implant was obtained by means of CAM software as shown in Fig. 3. Three dominant process parameters such as tool rotational speed, feed rate and step down were selected as shown in Table 2. The tool rotational speed and feed rate is an important parameter, which has effect on the heat generation due to friction with the sheet. The low speed and high feed rate is more suitable to increase the formability of the titanium alloy sheet[13].

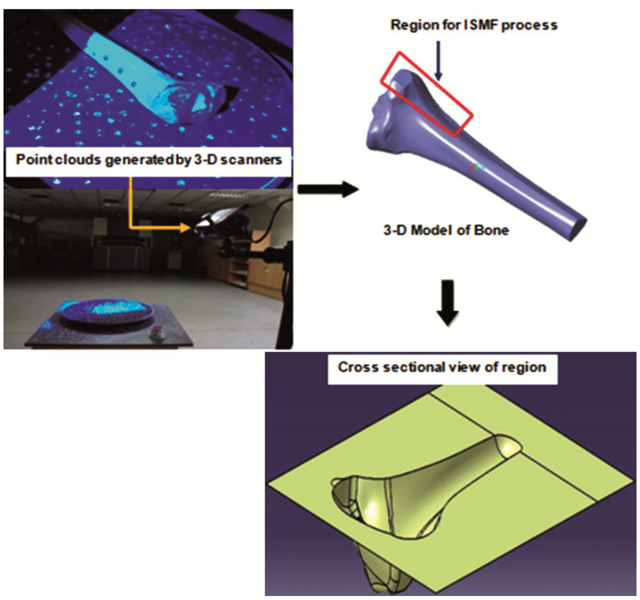

Fig. 2 — Generation of CAD model for region in knee bone.

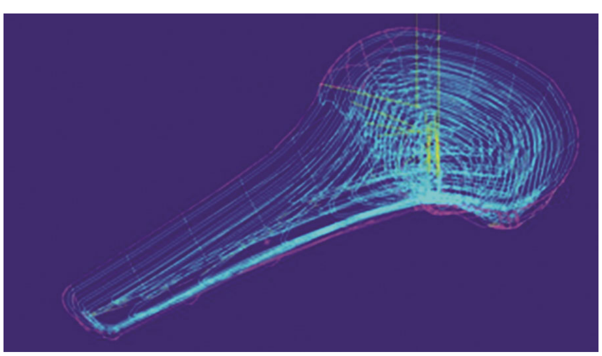

Fig. 3 — Tool path trajectory of knee implant.

2.3 Finite element modeling

Finite element analysis for incremental sheet metal forming technique was performed to avoid the possibility of multiple trials and to save the costs. FE analysis method was used to study the forming behavior of Titanium grade 2 sheets in ISMF process[20-22]. The SPIF process was simulated using ANSYS workbench by adopting adaptive meshing. The simulated tool movement matches real experiments including aspects such as rotation. FE model was built in ANSYS workbench by providing material properties obtained from the tensile test and tool path trajectory generated for the knee implant. Clamping edges of the sheet blank was constrained which is represented as region with white line in Fig. 4. Hemispherical rigid and roller ball forming tool of 10 mm diameter was used in FE simulation. The forming tool was considered as rigid body and the boundary conditions that should be followed during the process are given by the tool path. Roller ball tool with diameter of 10 mm other than the conventional rigid tool was employed in the finite element simulation. The sheet was assumed to be isotropic and the plastic property was modelled by means of Swift's isotropic strain hardening law[23].

Coulomb's friction law with a friction coefficient equal to 0.1 was adopted throughout the process and this value is commonly assumed in well lubricated sheet forming[24]. The entire geometry was selected for mesh generation and total number of elements observed was approximately 40,000 elements with mesh size of 1 mm. The following assumptions were made for finite element simulation[25],

Table 2 — Process parameters

Parameters	Values
Tool rotational speed	50 rpm
Feed rate	1000 mm/min
Step down	0.2 mm

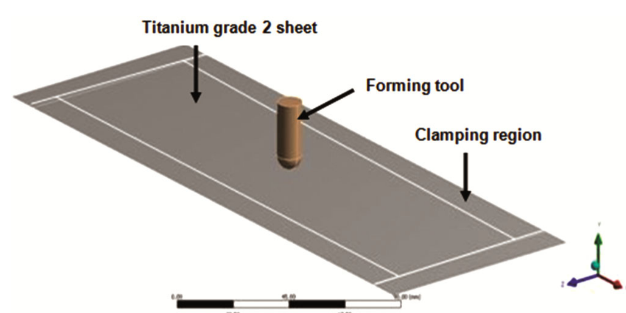

Fig. 4 — Assembly of sheet metal and forming tool geometry for finite element analysis.

(i)Temperature of sheet metal blank is kept constant throughout the process simulation.

(ii)There is no heat transfer between sheet metal and tool.

2.4 Experiment setup

Experiment was conducted by using a 3-axis vertical milling machine on Titanium grade 2 sheets of 1 mm thickness, where the sheet was mounted between clamping plate and backing plate on a modular fixture. All the four edges of the sheet were clamped using c-clamps as shown in Fig. 5. The modular fixture used in this work consists of a clamping plate, backing plate, support columns and a lower base plate. Conventional hemispherical rigid tool and the roller ball tool of 10 mm diameter were used for comparison as shown in Fig. 6. The forming tool follows the tool path trajectory during the SPIF process and the sequence of fabrication steps are shown in Fig. 7. The experiments were carried out at room temperature and the forming forces were measured using a table-type dynamometer. The dynamometer, when mounted under the forming fixture, can record forces that occur during the SPIF process. The forming force in three directions was measured by a Kistler 9129AA type dynamometer.

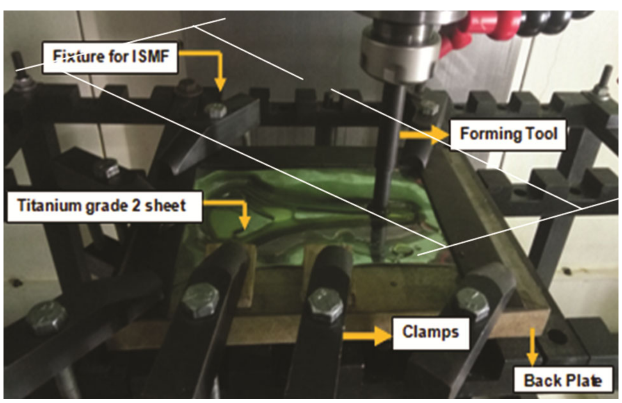

Fig. 5 — Experimental setup of SPIF on Ti grade 2 sheet.

Fig. 6 — Profile of the forming tools.

3 Results and Discussion

3.1 Forming forces

The incremental forming forces observed from finite element simulation and experiments were obtained and it can be seen that forming load variations follows similar path as shown in Fig. 8. From the graph it is observed that the forming forces are minimum at the initial stage of the process and it gradually increases when step depth value increases. The variation in forming loads depends on step depth value and tool path trajectory traced for component geometry. The maximum forming load observed is 690 N, which clearly describes that load required to produce parts are relatively less when compared with other process to manufacture the knee implant.

3.2 Sheet deformation

Distribution of strain on the incrementally formed knee part is obtained by finite element model

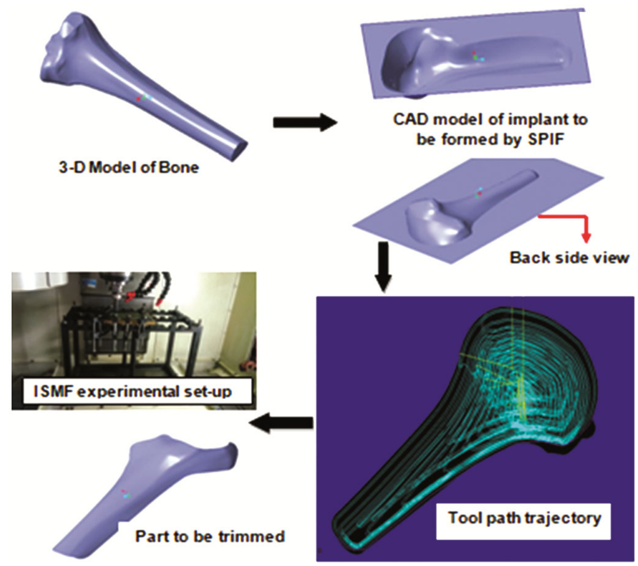

Fig. 7 — Fabrication steps involved in SPIF process.

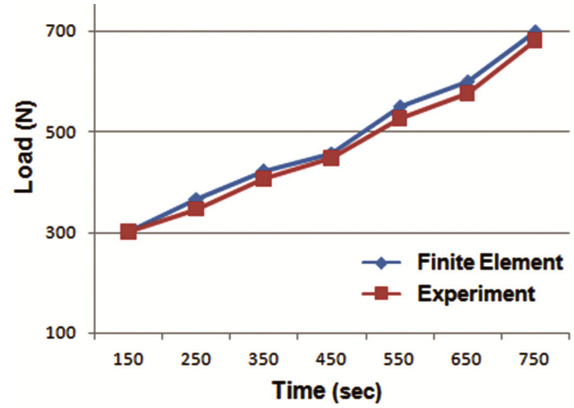

Fig. 8 — Forming load comparison.

simulated using ANSYS workbench. Presence of varying wall angle can be indentified in part geometry, however forming of a varying wall angle poses a greater challenge because of the strain distribution in the forming region. At the edges of the knee part, maximum deformation is observed due to the steep wall angle as shown in Fig. 9. Deformation is comparatively less in the regions other than edges because of smaller wall angle.

3.3 Profile accuracy and sheet thickness

Profile accuracy of the knee implant manufactured by ISMF process was measured by Mitutoyo CRYSTA Apex S 544 Coordinate Measuring Machine (CMM), which has measurement accuracy of 0.0001 mm. The primitive geometry of a component was defined by taking measurements at many locations. The coordinate measuring machine experimental setup for measuring profile accuracy is shown in Fig. 10.

The geometrical dimension of the part produced by roller ball tool through experimental approach is measured by CMM and compared to the nominal part model as shown in Fig. 11. It is observed that maximum deviation of 0.5 mm is from the edge of the part. This deviation may be due to the reduced stiffness at the edges. Geometrical difference between finite element analysis results and nominal part model is evaluated and found that bottom region of the implant has minor profile deviation of 0.5 mm due to the unreliable spring back prediction in finite element analysis. This result clearly suggests that geometrical compensation to smaller amount must be made to knee implant to eliminate the profile error after the ISMF process.

Thickness of the part processed by both hemispherical and roller ball tool were measured using CMM. Thickness distribution of the parts produced by hemispherical and roller ball tool through experimental approach shows identical thickness value, where thinning occurs at the edges of the knee implant at the bottom region. The initial sheet thickness is 1 mm, minimum wall thickness measured is 0.84 mm resulting in a 16% thickness reduction.

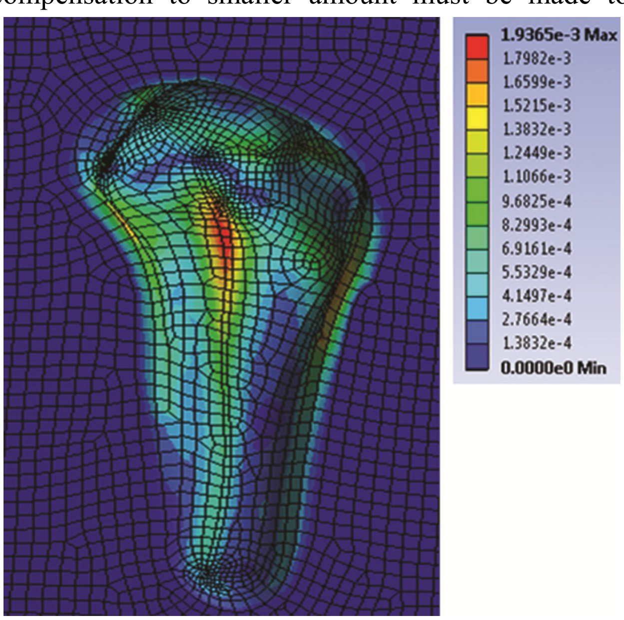

Fig. 9 — Distribution of equivalent strain.

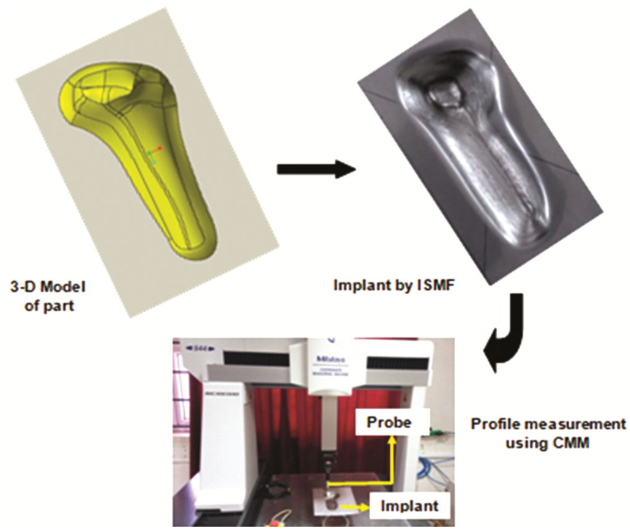

Fig.10 — Measurement and evaluation of formed knee part.

Fig. 11 — Comparison of the formed part with nominal design.

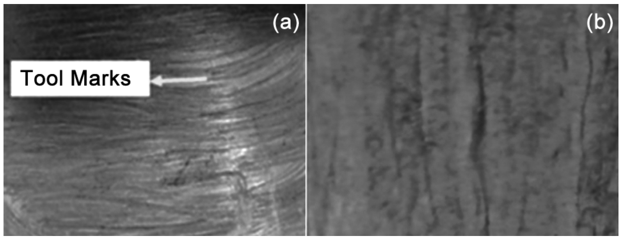

Fig. 12 — Surface examination of part (a) Hemispherical rigid tool, (b) Roller ball tool.

3.4 Surface finish

Surface finish of the part manufactured by ISMF process is examined and it is observed more galling on surface of the part formed by rigid hemispherical tool compared to roller ball tool as shown in Fig. 12. This is due to adhesion of tool and sheet metal, which causes wear and tool marks surface on the part. The knee implant produced by roller ball tool has high surface finish because of absence of adhesion between tool and sheet metal. Surface roughness tester Mitutoyo SJ201P equipment model was used to measure the surface roughness of the part produced by rigid hemispherical tool and roller ball tool. The cut-off length and evaluating length were fixed as 0.8 mm and 3 mm respectively. The R_z value of the part processed by the rigid tool is 26.5 µm as compared to that of 6.3 µm processed by the roller ball tool. The similar trend of difference of proportion of R_a value is obtained. It shows that surface finish of the part formed by roller ball tool gives better results than part formed by rigid hemispherical tool.

4 Conclusion

In this work, forming behavior of Titanium grade 2 materials has been studied by finite element simulation and experimental work for knee implant. Major conclusions of this research work have been presented below,

Incremental forming technique has been explored for manufacturing knee implant plate by using Titanium grade 2 sheet metal and it clearly shows the greater feasibility of the process for bio-medical applications.

The geometry of the knee implant has been evaluated using Coordinate Measuring Machine (CMM), where the geometrical accuracy of the part has been found satisfactory.

Thus the new process of forming sheets without using Die and Punch has been successfully carried out and demonstrated on titanium grade 2 for medical applications.

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