STEP AP 242 Managed Model-based 3D Engineering: An Application Towards the Automation of Fixture Planning

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Abstract: Fixture design and planning is one of the most important manufacturing activities, playing a pivotal role in deciding the lead time for product development. Fixture design, which affects the part-quality in terms of geometric accuracy and surface finish, can be enhanced by using the product manufacturing information (PMI) stored in the neutral standard for the exchange of product model data (STEP) file, thereby integrating design and manufacturing. The present paper proposes a unique fixture design approach, to extract the geometry information from STEP application protocol (AP) 242 files of computer aided design (CAD) models, for providing automatic suggestions of locator positions and clamping surfaces. Automatic feature extraction software "FiXplan", developed using the programming language C#, is used to extract the part feature, dimension and geometry information. The information from the STEP AP 242 file is deduced using geometric reasoning techniques, which in turn is utilized for fixture planning. The developed software is observed to be adept in identifying the primary, secondary, and tertiary locating faces and locator position configurations of prismatic components. Structural analysis of the prismatic part under different locator positions was performed using commercial finite element method software, ABAQUS, and the optimized locator position was identified on the basis of minimum deformation of the workpiece. The area-ratio (base locator enclosed area (%)/work piece base area (%)) for the ideal locator configuration was observed as 33%. Experiments were conducted on a prismatic workpiece using a specially designed fixture, for different locator configurations. The surface roughness and waviness of the machined surfaces were analysed using an Alicona non-contact optical profilometer. The best surface characteristics were obtained for the surface machined under the ideal locator positions having an area-ratio of 33%, thus validating the predicted numerical results. The efficiency, capability and applicability of the developed software is demonstrated for the finishing operation of a sensor cover – a typical prismatic component having applications in the naval industry, under different locator configurations. The best results were obtained under the proposed ideal locator configuration of area-ratio 33%.

Keywords: Standard for the exchange of product model data (STEP) application protocol (AP) 242, product manufacturing information, computer-aided fixture design, computer aided design (CAD)/computer aided manufacturing (CAM), automation, computer integrated manufacturing, 3D surface roughness.

1 Introduction

Globally, product-based industries are transforming themselves as model-based enterprises driven by digital communications and smart networks. The model-based definition (MBD) of products is essential to enable smart manufacturing systems. In MBD, a digital 3D model serves as the core information source from the level of conceptualization to the disposal of products. These concepts are explained comprehensively in ISO 16 792 (2015)

by ISO TC 10 and ISO 10 303-242 (2014) by ISO TC 184. 3D models enable quick responses to design changes and can shorten the product development cycles via less errors, streamlined communication and better interface between design and manufacturing processes, thus making it superior to 2D drawings. Smart manufacturing industries are evolving and have started using 3D models for product realization[1]. These computer aided design (CAD)-based 3D models contain all the product-related details such as shape, size, form features, surface texture, geometrical, and dimensional tolerances. This encapsulated data in standard for the exchange of product model data (STEP) application protocol (AP) 242 file open the possibility of automation of downstream manufacturing functions such as process planning, fixture design, tolerance analyses, and inspection planning[2].

Feature extraction and recognition play a key role in

attaining this integration of design and manufacturing for the development of smart manufacturing modules for automation. Numerous research works have focused on this problem, and their findings are briefly covered. Sun et al.[3] presented approaches for feature extraction methods, based on the prior knowledge of workpieces that could aid the automation of manufacturing processes. Abouel Nasr and Kamrani[4] used files in initial graphics exchange specification (IGES) format as input and suggested an intelligent feature recognition methodology. They also observed that to achieve a proper integration between design and manufacturing, an efficient feature recognition program is needed. Bhandarkar and Nagi[5] suggested STEP AP 224 based form feature extraction of prismatic solids for process planning. Sunil and Pande[6] proposed an artificial neural network (ANN)-based feature recognition system, which generated the feature representation vectors using the boundary representation (B-rep) CAD model in ACIS format. These vectors were then used by the neural network as input for classification and prediction of the feature patterns, which in turn were used for computer numerical control (CNC) program generation. Sunil et al.[7] suggested a hybrid approach for prismatic machine parts, based on geometric reasoning for identifying the interacting features from B-rep CAD models by using base explicit feature graphs and non-base explicit feature graphs. Wang et al.[8] developed an oriented feature extraction and recognition approach for identifying the interacting concave-convex features in the cast and then machined parts for known free form surfaces. Armillotta[9] suggested a method for generating tolerance specification from product model data by analyzing the contact information between the part geometry and the assembly operations involved in the product. The developed software tool was used to select a datum reference for each part based on a rule-based geometric reasoning procedure. Hebbal and Mehta[10] suggested an ideal setup plan for machining a prismatic part by identifying the workpiece orientation and coming up with viable setup plans for machining the maximum number of features in a single setup. Nagarajan and Reddy[11] further emphasized the need for systems that are platform-independent and can recognize various design and manufacturing features required for feature recognition. They developed a system which gave more importance to machining and volume removal, on the basis of extracted data from the STEP file which was taken as the input.

Borkar and Puri[12] suggested the integration of CAD/computer aided manufacturing (CAM) by feature extraction from a STEP AP 224 file format. This methodology can be used for information-transfer between different CAD systems. Kumar et al.[13] proposed feature-based modeling and the identification of process parameters for computer aided process planning (CAPP) in micro-manufacturing of prismatic parts through feature recognition and extraction from the extensible markup language (XML) file format. Rameshbabu and Shunmugam[14] combined face adjacency and volume sub-

traction using a hybrid feature recognition method for CAPP. The input for the feature extraction method was collected in the STEP AP 203 format. Zhang et al.[15] proposed a STEP-NC based high-level NC machining simulation solution which can be integrated with computer-aided-design, process planning and manufacturing. In order to machine multiple fixture pallets, Borgia et al.[16] suggested a network part program approach based on STEP-NC data, which integrated the existing process planning method with nonlinear process planning for better management of available resources. Srivastava and Komma[17] developed a graphical user interface for the extraction of feature information available in STEP AP 224 format. On the basis of extracted information, using a rule-based approach, the different process planning parameters are selected and STEP-NC code is generated.

Zehtaban et al.[18] suggested a framework using the OPITZ coding to support the similarity and retrieval system that helps to identify similar models from a CAD database using the data extracted from the STEP file of CAD model. Lupinetti et al.[19] retrieved CAD assemblies in huge databases using an enriched assembly model, which encoded all the required data automatically extracted from the geometry and structure of a CAD model. Venu et al.[20] developed a feature recognition system to recognize B-spline surface features from STEP AP 203 neutral file format for application in tool path generation for STEP-NC (STEP AP 238). Danjou et al.[21] suggested a closed-loop manufacturing approach, based on the STEP-NC standard for managing knowledge from the CNC machine to be used in the CAM system. This enabled the CAM programming stage to acquire the most relevant information pertaining to the manufacturing feature recognition knowledge database. Le et al.[22] suggested extracting additive manufacturing features and machining features from existing and final parts using the feature extraction approach, for applications in process planning.

Ma et al.[23] suggested an effective approach based on virtual machining to merge CAD and CAM applications for actual tool path generation and feed rate schedules for reducing the machining time and production cost in complex end milling operation. Hadj et al.[24] suggested CAD-LAB©, a CAD-integrated system to automatically identify and extract data from CAD assembly model using the model based systems engineering (MBSE) tool which enhances the interoperability process between the CAD system and computer aided engineering (CAE) application. Gupta et al.[25] suggested a computer-aided tool for evaluation of manufacturability based on machining features extracted from a prismatic part in STEP AP 203 format. Kataraki et al.[26] suggested the classification of regular form features and developed an algorithm for automatic identification of interactive and compound features of the prismatic part for generative process planning. Deja and Siemiatkowski[27] suggested a computer-aided process planning for parts manufacture to optimally solve pro-

cess planning problems by identifying process alternatives and sequencing adequate working steps using the branch and bound concept of artificial intelligence. Fougères and Ostros[28] suggested intelligent agents with a three-phase feature recognition approach involving virtual extension and feature identification by using a multi-agent system for intelligent CAD modeling. Kannan and Shunmugam[29] recommended feature reasoning and feature recognition as a means for generating manufacturing information from STEP AP 203 format to be applied in 3D sheet metal processing. Rahmani and Arezoo[30] developed a hybrid hint-based approach for identifying the interacting features in milling. They decomposed the part graph and generated concave sub-graphs from which the features were recognized on the basis of the properties of the concave graph and node. All these research works invariably emphasized the need for feature extraction to integrate design and manufacturing.

The latest product data exchange specification, STEP AP 242 approved by ISO in 2014, covers both AP 203 and AP 214 engineering domains. This model includes product development, manufacturing, and support by enabling a digital model, where the designer can make a 3D model that contains not only geometric information but also additional information like tolerance and product manufacturing information (PMI) data that can be extracted for downstream applications such as CNC code generation, fixture design, and process planning. This study aims at developing a smart manufacturing software module for automatic fixture planning based on the file generated in STEP AP 242 format from the CAD model of a part.

A fixture can be defined as a device for locating, holding, and supporting a workpiece while the machining operation is carried out. To bridge the gap between various phases in the fixture-design process, an integrated model capable of automatic fixture design and planning can be very useful. The fixture planning needs to determine the positions during the fixture design phase by identifying the locating scheme and locating/clamping surfaces to restrict the required degrees of freedom[31]. Bansal et al.[32] developed a platform-independent STEP based automatic feature recognition (AFR) system, where the STEP AP 203 input file was used for extracting manufacturing information. Based on the feature extraction results, fixture planning for different setup was suggested. Bansal et al.[33] proposed modular fixture planning by identifying the feasible locating positions for a solid, taking input in IGES/STEP format. The importance of locating plane height in improving the modular fixture plan was emphasized in this research work. Hunter et al.[34] pointed out the need for a functional approach to automate the fixture design process. They suggested that functions such as position, orientation, clamping and support associated with the fixture design process need to be considered for automation. Parvaz and Nategh[35] developed a python program based integrated computer engineering platform

for automated fixture design. This platform combined various specialized modules involved in computer-aided fixture design. Rex and Ravindran[36] proposed an iterative design of experiment and finite element method (FEM) approach for fixture layout and multi-constrained optimization for reducing the workpiece deformation in prismatic components.

The following observations were made after the comprehensive literature survey. Automatic feature extraction is an important component of CAD/CAM integration. The existing studies deal with feature extraction from IGES[4, 33], STEP AP 203[14, 20, 25, 29, 32], STEP AP 224[5, 12, 17], STEP AP 238[20], etc. STEP AP 242 has been selected as the data exchange standard for managed model based 3D engineering from 2014[2]. Most of the commercial softwares have incorporated STEP AP 242 in their latest versions for the standardization of CAD data with industrial applications. However, a detailed automatic feature extraction module for STEP AP 242 was not found in literature. An attempt is made in the present work to bridge this gap through the development of the FiXplan software. The developed software has the capability to suggest the locator position from the component dimensions. The present work deals with automatic fixture planning by suggesting the clamping surfaces, and locator positions of prismatic components based on STEP AP 242. Furthermore, in the previous works, locator positions were selected arbitrarily, whereas in this study, a logical approach is employed to select the locator positions based on the work piece dimensions. This enables the suggestion of ideal locator positions based on the ratio of area enclosed by locators to total area of the surface, making it a more generalized approach in fixture design by automatic feature extraction.

The present work aims at developing a smart manufacturing system module for automatic fixture design planning that is capable of identifying the primary, secondary, and tertiary locating faces of prismatic components and also the clamping surfaces. FEM based simulation and experimental verification are used to ensure the prediction-capability of the developed software module. Section 2 of the paper describes in detail the methodology adopted for this study and the development of the software module (FiXplan). Section 3 presents the simulation study for fixture planning, while Section 4 covers the experimental validation. A case study is presented in Section 5 for demonstrating the proposed approach of fixture planning, and Section 6 presents the conclusion.

2 Methodology

In this study, the part design is performed using commercially available CAD software, CATIA V6, in which the part is represented as a solid model using the B-rep technique. The various primitives of the solid model, dimensional and geometric information represented in STEP AP 242 format are used as input to the developed software. This makes the methodology platform-inde-

pendent, which enables it to communicate with various CAD/CAM systems. The dimensional and geometric information stored in the STEP AP 242 file are analyzed by the feature recognition and extraction software program developed using C#. The features of the part like slots, pockets, holes, conical surfaces, spherical surfaces, etc. have been extracted using the geometrical reasoning approach. These extracted part features are used to suggest fixture planning for a prismatic component. The 3-2-1 fixturing scheme is used to locate and hold the prismatic workpiece[37]. FEM based simulation is conducted for identifying the optimal locator configuration for a prismatic part that gave the minimum part deflection. The identified optimum locator configuration based on FEM simulation is incorporated in the software module. It helps in suggesting optimal configuration of locators and clamps for maintaining minimum deformation of the workpiece during machining operation. The results are experimentally verified by conducting milling experiments on prismatic parts using specially developed fixtures. Fig. 1 shows the overview of the methodology followed in the present study.

2.1 Step file schema

The STEP format is used to exhibit the data of the part made using the CAD software that is represented as boundary representation (B-rep) in the CAD model. Boundary representation describes the object in terms of its boundaries viz. face, edge, and vertex and gives the orientation of each surface and its geometry. The developed feature extraction and fixture planning software (FiXplan) extracts the geometry and topology information from the STEP file and stores the data in class files.

The CAD model is represented in the STEP architecture as a closed shell. The closed-shell includes the details of the advanced faces that make the object, shape orientation, and axis location. The advanced face comprises data regarding the face outer bound (FOB) and face bound (FB), and based on this, the exterior loop and the interior loop can be identified. The FOB and FB contain the details of edge loop topology, which constitutes the advanced face. The edge loop contains information about the oriented edge and edge curve. The orientation of the edge in the anti-clockwise direction is denoted as true, and false is assigned for the same in the clockwise direction. The edge curve direction is taken as true for positive X, Y and Z axis in STEP file and false for negative direction. It is based on the right-hand thumb rule where the fingers point in the positive directions of the axes. The edge curve also contains information about line origin and vector line direction. The line direction is denoted as $+1$ for positive axis direction and -1 for negat-
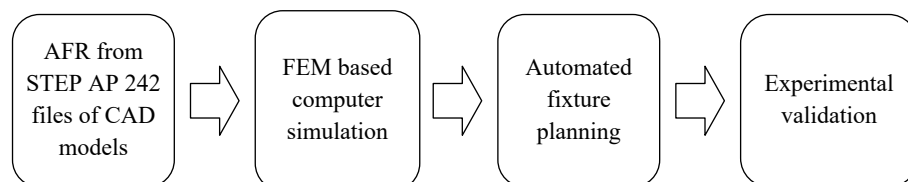

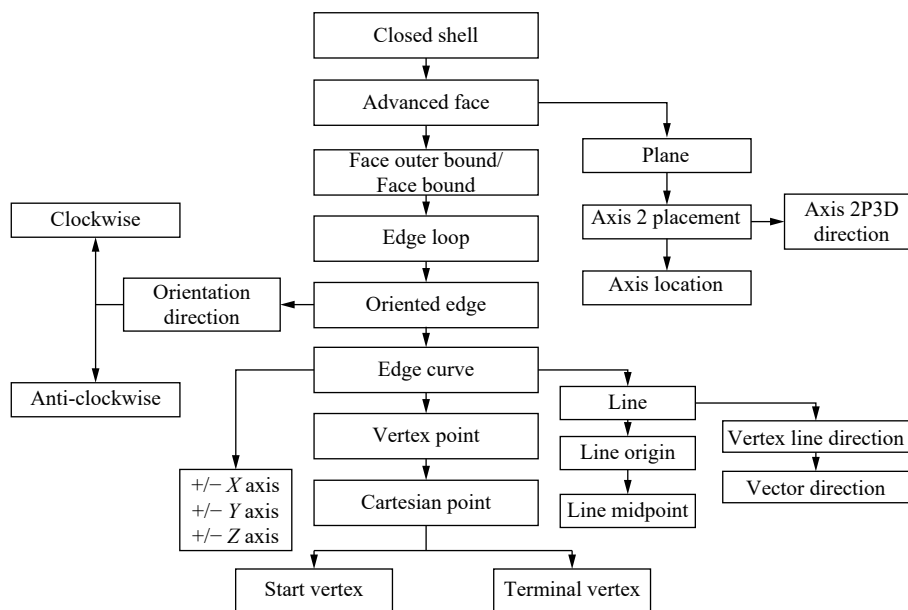Fig. 1   Methodology adopted in this work

Fig. 2   STEP file schema

ive axis direction. The lowermost denomination of the STEP structure is the starting and terminal vertex which constitutes the edge. The schematic of the STEP file structure is shown in Fig. 2.

2.2 Feature extraction from STEP AP 242 file

The orientation of the edge and the face direction are the basic information needed to extract the features from the STEP file. The edge orientation is obtained as output in the FiXplan software. The concave edge test, based on the vector cross product of the normal vectors of the two faces which share a common edge, is used to identify the concavity and the convexity. Each common edge E_n shared by the faces F_1 and F_2, the direction vectors N_1 and N_2 of the faces are denoted as in Fig. 3. The order followed when observed from the edge view perspective is from right to left.
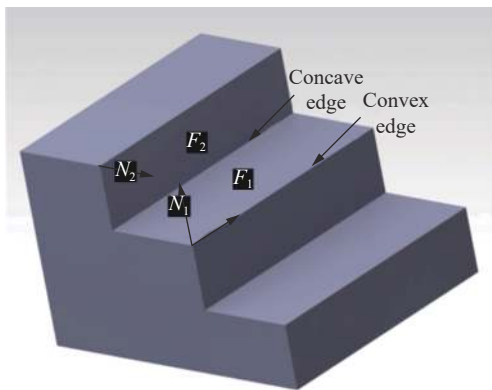

Fig. 3   Identification of concavity and convexity from part

The following is the methodology[4] for the concavity test:

1) Calculate the vector cross product (V) of the directional vectors of the faces using $V = N_1 \times N_2$.

2) The direction of the edge E_n with respect to the face F_1 is determined. In the aforementioned cross product, the first component should be the normal vector N_1 of face F_1.

3) If the direction vector of edge E_n from the preceding step is in the opposite direction of cross product V, then the edge E_n is the concave edge that concludes F_1 and F_2 as concave faces; otherwise, it will be convex edge and F_1 and F_2 become convex faces. If V is 0, it means the edge is a tangent.

This procedure is followed on all the edges of the part to define the concave, tangent, or convex faces. Moreover, concave features will be identified by the premise that concave faces include at least one concave edge with adjacent concave faces forming a concave face set. Similarly, adjacent convex faces form a convex face set.

Algorithm 1. Pseudocode for checking concavity

Input: Step file

Output: To identify edge loop concavity, convexity, and tangency

1) Procedure ( )
2) Read closed-shell
3) Count the number of advanced_ face
4) For each advanced_face
5)   Read surface_shape
6)   If surface_shape = plane then
7)   Read number of edge_loop
8)   For each edge_loop
9) $StartX[i]$ = Start_vertex.Xcoordinate
10) $StartY[i]$ = Start_vertex.Ycoordinate
11) $StartZ[i]$ = Start_vertex.Zcoordinate
12) $EndX[i]$ = End_vertex.Xcoordinate
13) $EndY[i]$ = End_vertex.Ycoordinate
14) $EndZ[i]$ = End_vertex.Zcoordinate
15)   End
16) $Edge\ Length\ [i] =$

$$\sqrt{(EndX\,[i] -\ StartX[i])^2 + (EndY\,[i] -\ StartY\,[i])^2 + (EndZ\,[i] -\ StartZ\,[i])^2}$$

17)   End
18) End
19) //*Finding common edge*//
20) For each pair of advanced_ face i, j do
21)   If ($StartX[i] = StartX[j]$ &&$StartY[i] = StartY$ $[j]$ &&$StartZ[i] = StartZ[j]$&&$EndX[i] = EndX[j]$ && $EndY[i] = EndY[j]$&&$EndZ[i] = EndZ[j]$) then
22)   Add edge_loop to Common_ edge[i]
23)   End
24) End
25) //*Finding concavity*//
26) For each pair of advanced_ face i, j
27)   Edge.Concavity = unknown
28)   Cross_product=Face[i].Normalvector$\times Face[j]$. Normal vector
29)   If Cross_product = 0
30)   Edge.Concavity = Tangent
31)   Else
32)   Compare the direction of oriented_edge for the line with respect to the loop
33)   If cross_product is in the same direction as oriented_edge
34)   Edge.Concavity = Convex
35)   Else
36)   Edge.Concavity = Concave
37)   End
38)   End
39) End

Fig. 4 shows the flowchart for determining the concavity of the edges of a part. The extraction of various features is attempted and the results are explained below:

Prismatic block. The developed software is used to extract the geometric dimensions of the given part as shown in Fig. 5. An output is generated that prints the surface type which forms the part. Face outer bound and face bound give the information regarding the outer loop and inner loop for each advanced face. For each edge loop
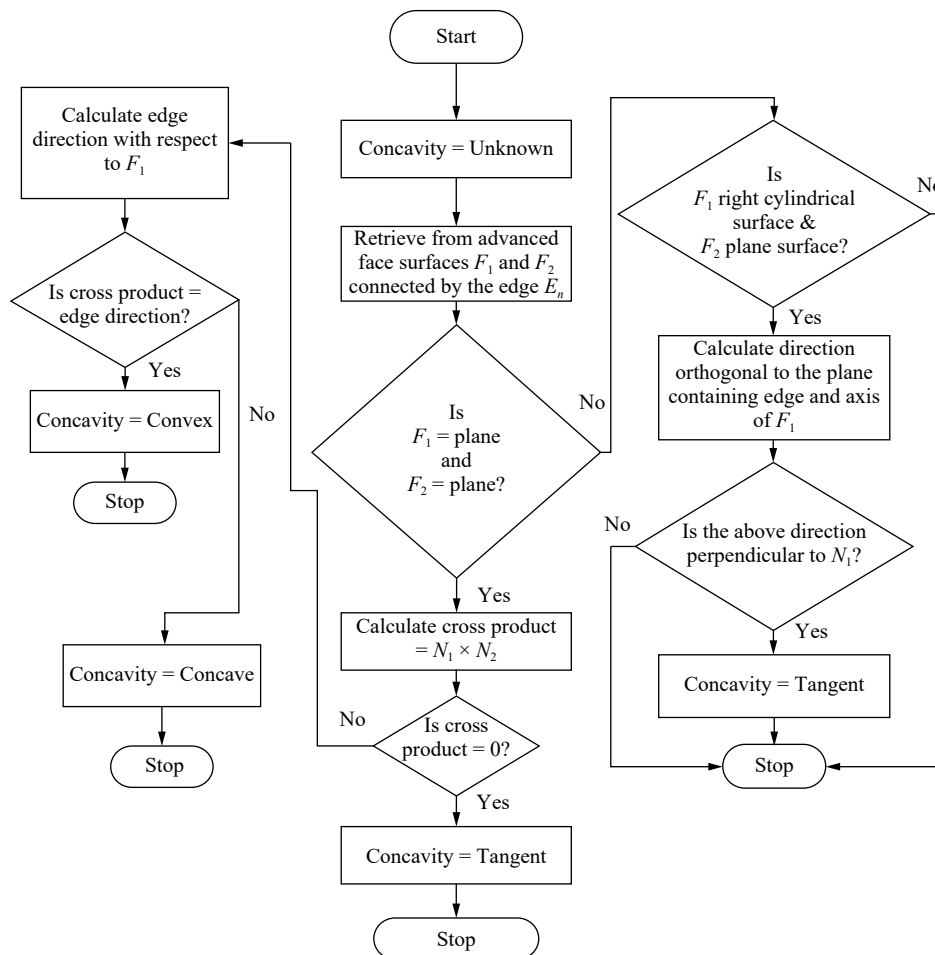
Fig. 4   Flowchart for determining the concavity of the edge

in the advanced face, the program prints the value of the maximum and minimum x, y, and z coordinate values in absolute terms by reading the STEP file of the part, as shown in Fig. 5. The coordinate values are checked between maximum and minimum values, and from the edge loops for the various faces, the edges having common end coordinates can be printed. This gives a list of common edges and the faces which share this common edge.

Hole feature. The output for the cylindrical hole features viz. blind, through or stepped (Figs. 6(b) and 7(a)) can be obtained from the program developed. From Figs. 6(b) and 7(b), there are six planar faces, and two cylindrical half faces F_1 and F_2. for the feature. The face bound flag corresponding to the advanced planar face, suggests the presence of two inner loops for a through-hole. In the case of a cylindrical protrusion (Fig. 6(a)), only one inner loop is identified, as the face bound flag is raised for only one planar face. To distinguish between a cylindrical protrusion and a cylindrical hole, the test for concavity is done at the inner loop edge. Based on the output obtained, the radius of the circle, the height or depth of the hole/protrusion can be calculated from the changing coordinate value (Z-coordinate).

For a stepped hole, there are four half-cylindrical surfaces F_6, F_7, F_9 and F_{10} as shown in Fig. 7(a). The output reveals that there are seven planar faces and three inner loops from the face bound flag. From the axis position of both the holes, the radius of the circle and the respective depth of the hole can be printed based on the changing coordinate value.

In the case of a countersunk hole, the output generated gives the two conical half faces F_1 and F_2, and the two cylindrical half faces F_3 and F_5, as shown in Fig. 8(a). The axis position gives the diameters of both larger and smaller holes, and the depth by calculating the varying coordinate value. The same applies to the conical or tapered hole shown in Fig. 8(b). Here, F_1 and F_2 represent the two conical half faces, which constitute the tapered hole, and the dimensions can be printed from the axis position and the measurement of the varying coordinate value. The face bound flag denotes the planar face, which has the inner loop.

Pocket feature. The pocket feature can be identified from the face loop by extracting the dimensions of the constant value coordinate and the changing coordinate value in a face. The face bound flag denotes which face has an inner loop, and if it is a blind pocket, only
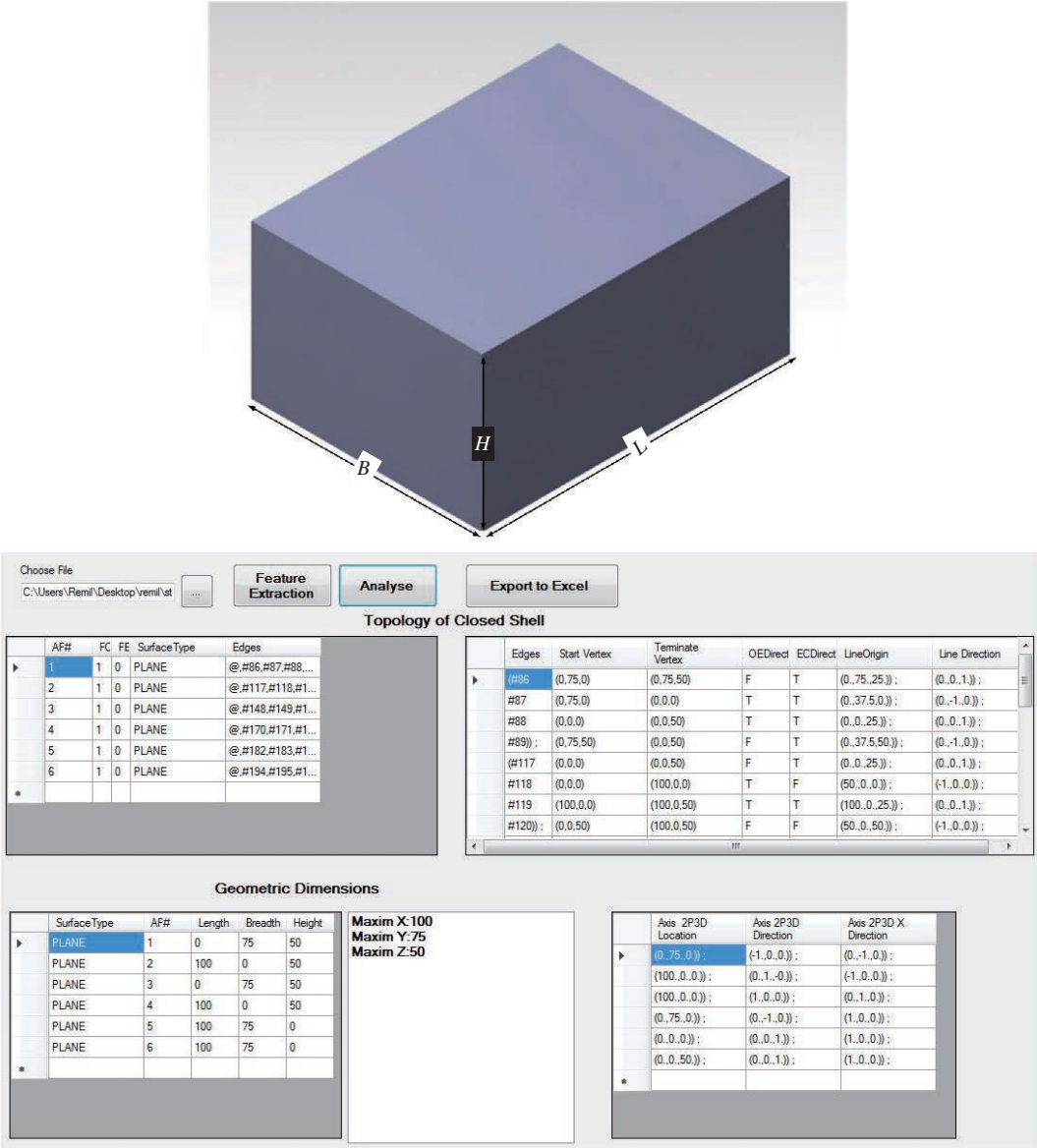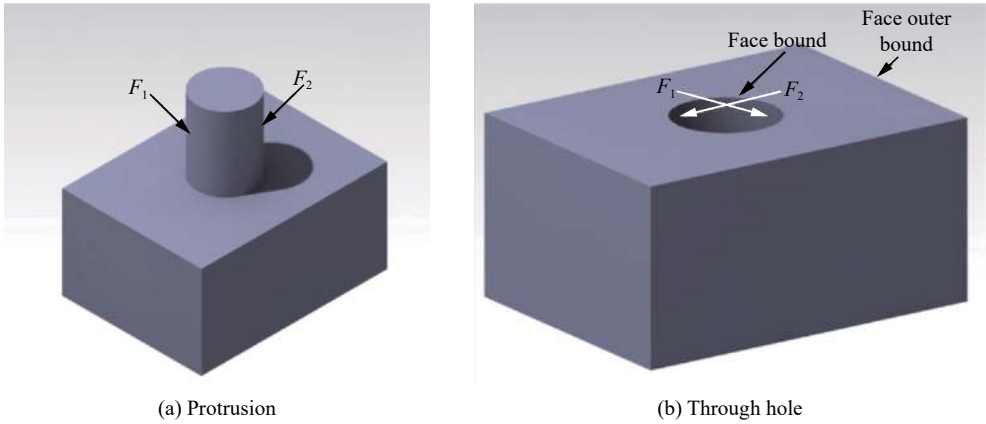
Fig. 5   Feature extraction from a prismatic model

Topology of Closed Shell

AF#	FC	FE	SurfaceType	Edges
1	1	0	PLANE	@,#86,#87,#88,...
2	1	0	PLANE	@,#117,#118,#1...
3	1	0	PLANE	@,#148,#149,#1...
4	1	0	PLANE	@,#170,#171,#1...
5	1	0	PLANE	@,#182,#183,#1...
6	1	0	PLANE	@,#194,#195,#1...

Edges	Start Vertex	Terminate Vertex	OEDirect	ECDirect	LineOrigin	Line Direction
(#86	(0,75,0)	(0,75,50)	F	T	(0.,75.,25.)) ;	(0.,0.,1.)) ;
#87	(0,75,0)	(0,0,0)	T	T	(0.,37.5,0.)) ;	(0.,-1.,0.)) ;
#88	(0,0,0)	(0,0,50)	T	T	(0.,0.,25.)) ;	(0.,0.,1.)) ;
#89)) ;	(0,75,50)	(0,0,50)	F	T	(0.,37.5,50.)) ;	(0.,-1.,0.)) ;
(#117	(0,0,0)	(0,0,50)	F	T	(0.,0.,25.)) ;	(0.,0.,1.)) ;
#118	(0,0,0)	(100,0,0)	T	F	(50.,0.,0.)) ;	(-1.,0.,0.)) ;
#119	(100,0,0)	(100,0,50)	T	T	(100.,0.,25.)) ;	(0.,0.,1.)) ;
#120)) ;	(0,0,50)	(100,0,50)	F	F	(50.,0.,50.)) ;	(-1.,0.,0.)) ;

Geometric Dimensions

SurfaceType	AF#	Length	Breadth	Height
PLANE	1	0	75	50
PLANE	2	100	0	50
PLANE	3	0	75	50
PLANE	4	100	0	50
PLANE	5	100	75	0
PLANE	6	100	75	0

Maxim X:100
Maxim Y:75
Maxim Z:50

| Axis 2P3D Location	Axis 2P3D Direction	Axis 2P3D X Direction
(0.,75.,0.)) ;	(-1.,0.,0.)) ;	(0.,-1.,0.)) ;
(100.,0.,0.)) ;	(0.,1.,-0.)) ;	(-1.,0.,0.)) ;
(100.,0.,0.)) ;	(1.,0.,0.)) ;	(0.,1.,0.)) ;
(0.,75.,0.)) ;	(0.,-1.,0.)) ;	(1.,0.,0.)) ;
(0.,0.,0.)) ;	(0.,0.,1.)) ;	(1.,0.,0.)) ;
(0.,0.,50.)) ;	(0.,0.,1.)) ;	(1.,0.,0.)) ;

(a) Protrusion   (b) Through hole

Fig. 6   Cylindrical features

one face will be having a face bound. In the case of a through pocket, both the planar faces will show an inner loop, and by checking parallel and perpendicular faces for the inner loop, the faces can be identified. The changing coordinate value along the z-direction is taken as height or depth, and the varying value of the other two coordin-
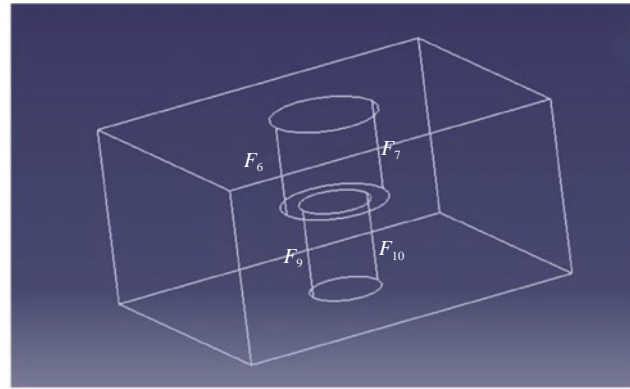
(a)
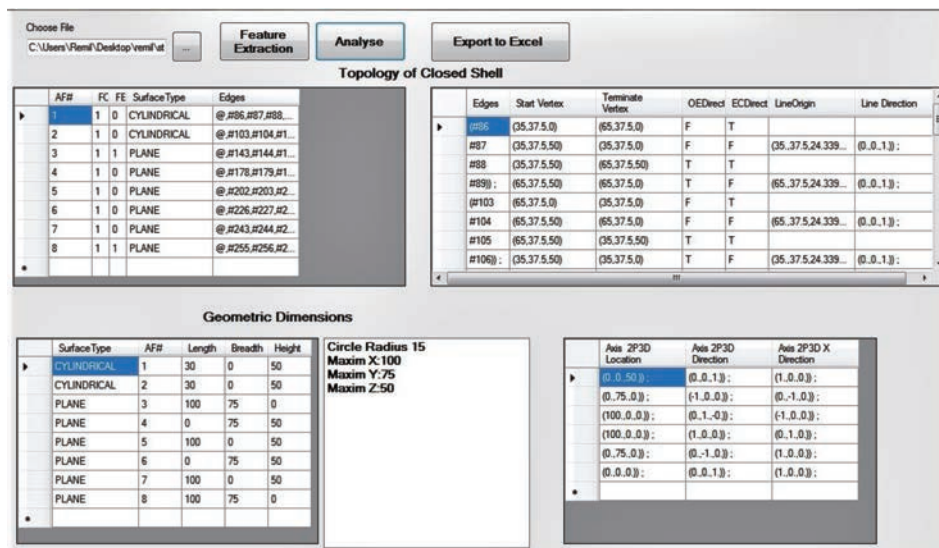
(b)

Fig. 7   Feature extraction of the stepped hole: (a) Stepped hole; (b) Extraction of features of the through-hole

ates inside a planar outer bound gives the length and breadth of the pocket in the inner loop.

Slot feature. The dimensions of the slot feature can be extracted by finding the varying dimensions taken along different coordinates as length, breadth, and depth of the slot feature. Fig. 9 shows F_1 and F_3 as parallel faces, while F_2 is perpendicular to both. The parallel faces and perpendicular faces can be identified from the direction of the normal face vector and the concavity test is done at the common edge for the planar face to identify the slot feature. The concavity test is described in Fig. 4. To test the capability of the software, a geometry containing multiple features is modeled, and the features are extracted from the generated STEP AP 242 file. The result obtained is given in Fig. 10, where the model and the feature extraction capability of the software are depicted.

Thus, by observing the output obtained from FiXplan, it is proved that the software is capable of extracting any surface feature. The extracted features and dimensions are used for automated fixture planning of prismatic parts.

3   Simulation study for fixture planning

In fixture planning, based on the component size and dimensions, the locator positions are proposed, and the accuracy of the proposed positions are validated numerically and experimentally. Li and Melkote[38] developed an algorithm for clamping force optimization based on workpiece location accuracy, with a contact mechanics model for force calculation. In accordance with this study, an experiment is performed on a four-axis vertical machining centre (Make: Bharat Fritz Werner Ltd., Model: Agni BMV 45 TC24) to determine the maximum force applied on a prismatic component. To provide realistic values of cutting forces for the simulation study, machining experiments were performed on an Al-7 075 based prismatic part (Fig. 11), and the actual cutting forces were measured. A multi-component force dynamometer (Kistler 9257B) was used for the purpose of force measurement during the machining operation. The forces at each instant (Fx, Fy. and Fz) were obtained from the dynamometer, and the maximum Fx, Fy, and Fz values for machining Al-7 075 workpiece were observed as 66.22 N,
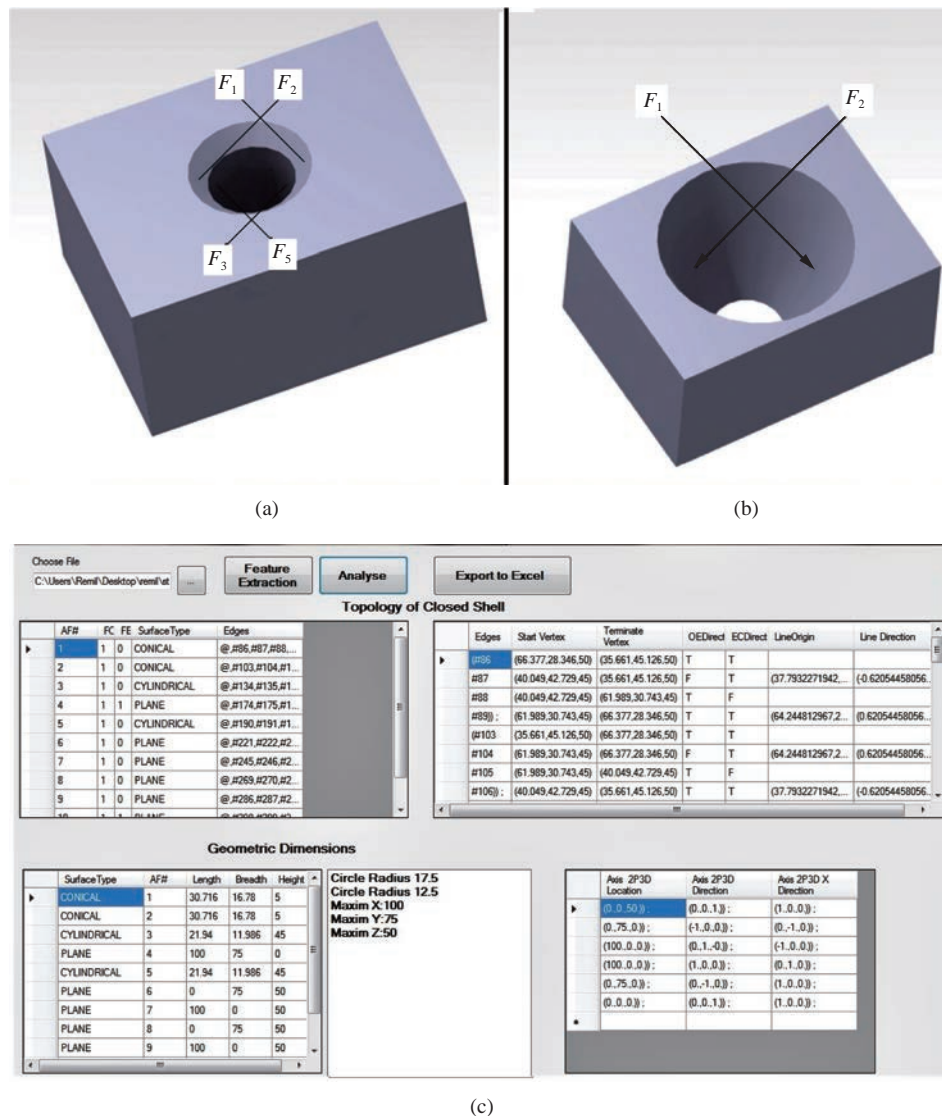
(a)

(b)

(c)

Fig. 8   Feature extraction and recognition: (a) Countersunk hole; (b) Conical hole; (c) Feature extraction of countersunk hole
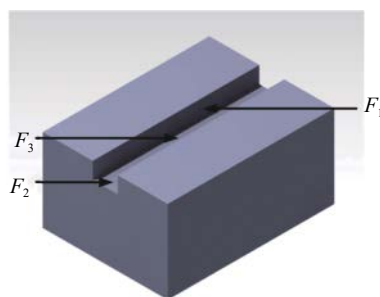

Fig. 9   Slot feature

71.10 N and 63.47 N, respectively. This force data was used for numerically simulating the nodal displacement during FEM based analyses under different locator combinations. For the prismatic component, the locator configuration of 3−2−1 was used to arrest the required degrees of freedom. To check the validity of this proposal, numerical simulation of the nodal displacement under different locator combinations was attempted. The locator positions for putting the locator pins are shown in the fixture plate, and locator pins can be changed based on the position mentioned in Table 1. For the first combination, locators L_1 and L_2 positions are taken as 5% of x dimension from both extremes, 5% of y dimension of the component and z is taken as minimum value as it is on the bottom surface. L_3 locator is positioned along the symmetry line for the x dimension and 5% of the y dimension taken from the maximum y value and z is taken as minimum as on the bottom surface. L_4 and L_5 are taken 5% of x dimension from both extremes and y is taken as the maximum value and z is taken along the centre line of symmetry. L_6 is taken as maximum x value and symmetry centre lines for y and z dimensions. Similarly, other combinations are fixed based on the dimensions of the work piece. The 3D numerical model of the part was simulated and analyzed using ABAQUS software.
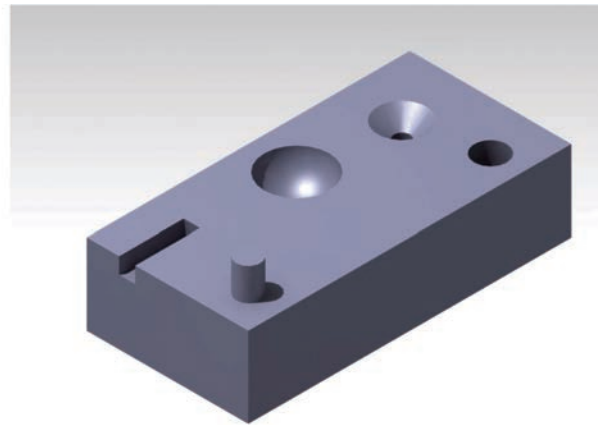
(a)
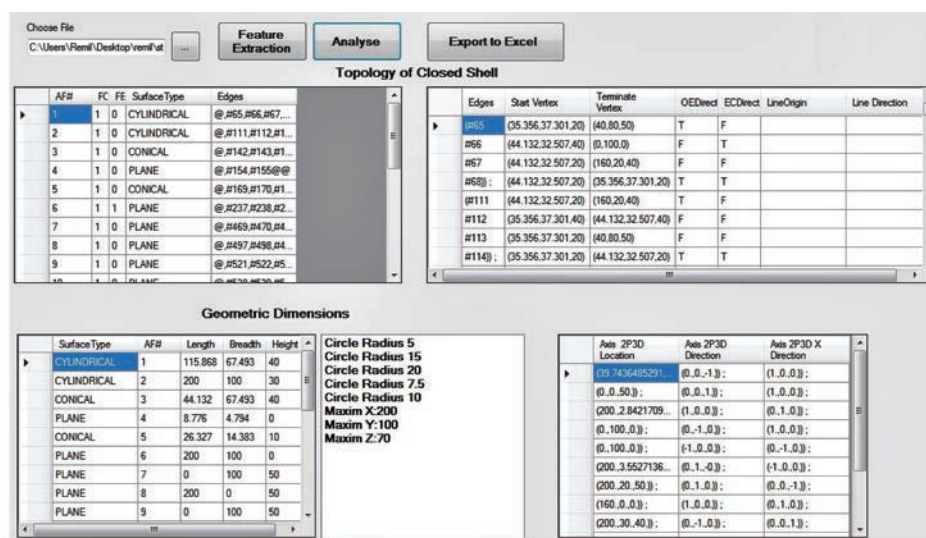
(b)

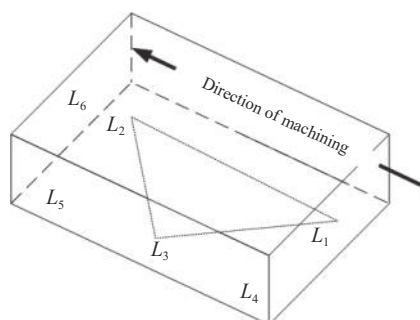Fig. 10   Multi-feature component: (a) CAD model; (b) Feature extraction

Fig. 11   Prismatic component with the 3-2-1 locator position

A prismatic block of dimension $150\,\text{mm}\times100\,\text{mm}\times50\,\text{mm}$ is used for the analysis. The experimentally obtained loads were applied in 50 steps along the length of the workpiece. To replicate the actual machining conditions, the root mean square (RMS) value of the force is applied at one node for each time step, i.e., for the first step load acts on the first node and the load at all other nodes are zero and for the 15th time step, the load acts only on the 15th node and force on all the other nodes are made zero. Thus, the actual machining condition is simulated. A feed of $10\,\text{mm/min}$ is provided for the traverse of the tool along the workpiece of length 150 mm. The following steps are followed for the numerical analysis:

1) The tool is modeled as an instantaneous point load with its value equal to the RMS value of the force during that period obtained from the force measurement data.

2) The locator positions are modeled by finding the specific locations on the workpiece and applying the constraints $u_z = 0$ for the bottom locators (L_1, L_2, L_3), $u_y = 0$ for the side locators (L_4, L_5) and $u_x = 0$ for the other side locator L_6 (Fig. 11).

3) The instantaneous point load is traversed on the workpiece surface in a similar manner as the tool moves over the workpiece (Fig. 12).

4) The nodal displacement value at the locator points with respect to the tool movement is calculated.

The aforesaid four steps are repeated for all the prismatic components, and it is observed that the minimum displacement occurs at a locator configuration of 10% of

Table 1   Locator positions for inserting locator pins

$L_1\ (x, y, z)$	$L_2\ (x, y, z)$	$L_3(x, y, z)$	$L_4(x, y, z)$	$L_5(x, y, z)$	$L_6\ (x, y, z)$
$(7.5, 5, 0)$	$(142.5, 5, 0)$	$(75, 95, 0)$	$(7.5, 100, 25)$	$(142.5, 100, 25)$	$(150, 50, 25)$
$(15, 10, 0)$	$(135, 10, 0)$	$(75, 90, 0)$	$(15, 100, 25)$	$(135, 100, 25)$	$(150, 50, 25)$
$(22.5, 15, 0)$	$(127.5, 15, 0)$	$(75, 85, 0)$	$(22.5, 100, 25)$	$(127.5, 100, 25)$	$(150, 50, 25)$
$(30, 20, 0)$	$(120, 20, 0)$	$(75, 80, 0)$	$(30, 100, 25)$	$(120, 100, 25)$	$(150, 50, 25)$
$(45, 30, 0)$	$(105, 30, 0)$	$(75, 70, 0)$	$(45, 100, 25)$	$(105, 100, 25)$	$(150, 50, 25)$
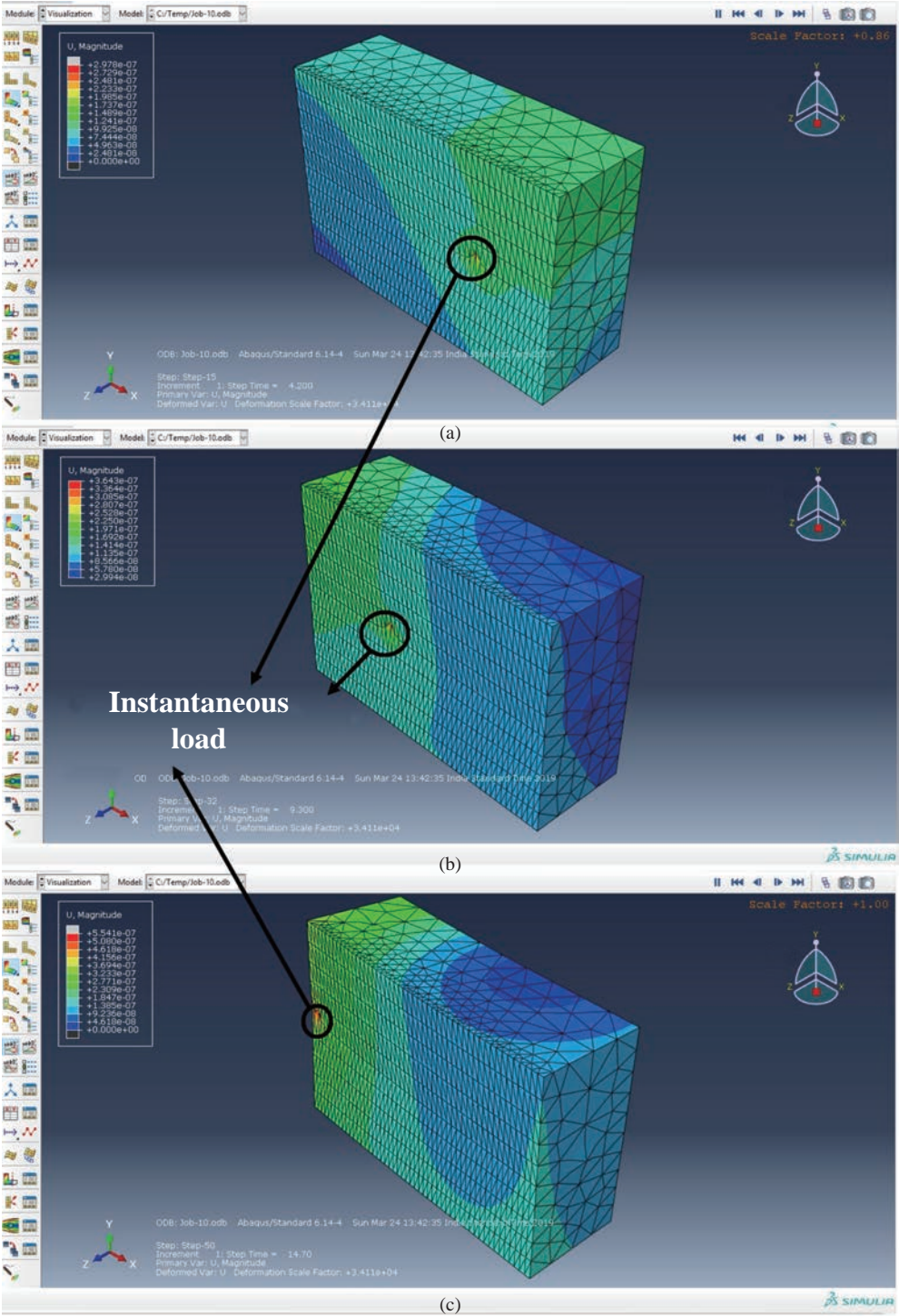
Fig. 12   Instantaneous load application on the workpiece at (a) $t = 5\,\mathrm{min}$; (b) $t = 10\,\mathrm{min}$; (c) $t = 15\,\mathrm{min}$

size for the primary face (L_1, L_2 and L_3), 10% of the size of the secondary face (L_4 and L_5) and 50% size for the tertiary face (L_6) (Table 2). Further, the simulation results show that 33% of an area ratio (triangular area of support to the total area of the primary face) is necessary for the minimum deformation of the part.

Hence, the numerical results suggest that the proposed locator combination gives the lowest nodal displacement and thus can be used as the locator configuration for the machining of prismatic parts. In order to validate this, surface characteristics (3D roughness and waviness) of the machined surfaces under different locator configurations of the fixture are analyzed further.

4 Experimental validation

Experiments were conducted on a four-axis CNC vertical machining center (AGNI BMV 45 TC24) to validate the simulation results.

For the various locator configurations, slots are machined on the prismatic 7 075 aluminium block of 150 mm × 100 mm × 50 mm using a specially designed fixture that has a provision for changing the locator positions shown in Fig. 13. An end mill cutter of 12 mm diameter is rotated at 700 rpm, with a feed and depth of cut of 10 mm/min and 1.5 mm, respectively.

The locator and clamping surfaces were automatically identified from the FiXplan software for a particular workpiece orientation. The surface roughness and waviness of the machined surface were measured using Alicona Infinite Focus G5, a non-contact 3D optical profilometer. In order to conduct the area measurements, a 20X lens was used. The lens has a lateral measurement area range of 0.61 mm². Multiple images of the end-milled slot were taken simultaneously and stitched together using the inbuilt image processing software to capture the entire slot in a single image. From the captured image, an area of 30 mm × 10 mm was taken for the measurement of areal surface roughness (Sa) and waviness. The measurement results are tabulated and given in Table 3 and Fig. 14.

From the results obtained, it can be observed that the best combination is noticed for the locator position of 10% of the dimension of the primary face and secondary face, and 50% of the dimension of the tertiary face. The 2D top view of the surface machined under the best locator configuration is shown in Fig. 15. Thus, the numerical and experimental results indicated that the ideal locator

Table 2   Maximum displacement for different locator combinations

Configuration	Base locator enclosed area/ Workpiece area (%)	Maximum displacement (μm)
$L_1L_2L_3$ @ 5%; L_4L_5@ 5%; L_6@ 50%	40.5	0.659 1
$L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50%	**33**	**0.609 6**
$L_1L_2L_3$ @ 15%; L_4L_5@ 15%; L_6@ 50%	24.5	0.619 6
$L_1L_2L_3$ @ 20%; L_4L_5@ 20%; L_6@ 50%	18	0.666 9
$L_1L_2L_3$ @ 30%; L_4L_5@ 30%; L_6@ 50%	8	0.806 1

Table 3   Experimental observations for machining of the prismatic part

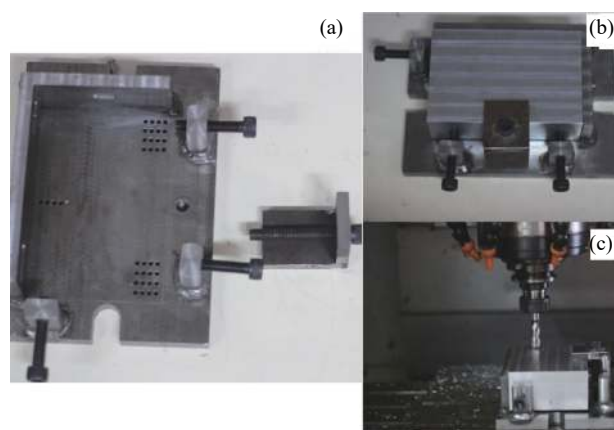| Sl No.	Configuration	Areal surface roughness (μm)	Waviness (μm)
1	No locator (Trial experiment for force measurement)	3.485 6	2.186 2
2	**$L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50%**	**2.945 6**	**0.879 5**
3	$L_1L_2L_3$ @ 15%; L_4L_5@ 15%; L_6@ 50%	2.996 9	1.253 7
4	$L_1L_2L_3$ @ 20%; L_4L_5@ 20%; L_6@ 50%	3.558 2	1.672 2
5	$L_1L_2L_3$ @ 30%; L_4L_5@ 30%; L_6@ 50%	3.304 5	1.484 2
6	$L_1L_2L_3$ @ 5%; L_4L_5@ 5%; L_6@ 50%	3.089 9	1.352 5

Fig. 13   Specially designed fixture: (a) Fixture plate; (b) Prismatic block fixed in the fixture; (c) Actual machining on the prismatic component
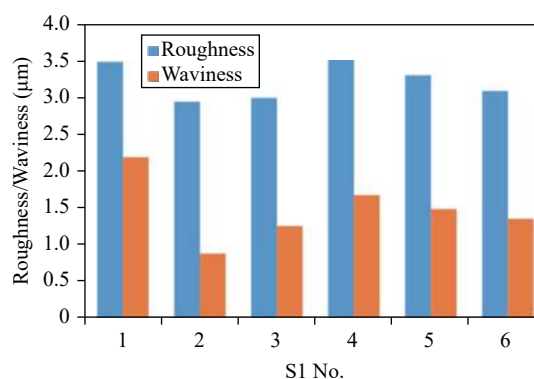

Fig. 14   Roughness and waviness readings for different locator configurations during the machining of the prismatic part

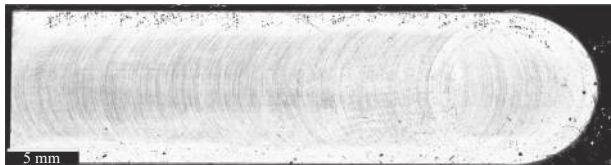Fig. 15   Image of the machined slot obtained using 3D non-contact optical profilometer at $L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50% location configuration

configuration for obtaining the best machining is $L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50% of the dimensions of the respective faces.

5   Case study

The developed software was used to propose fixture planning in the machining of a sensor cover, used for housing the circuit board in the naval application (Fig. 16). The STEP AP 242 file derived from the CAD
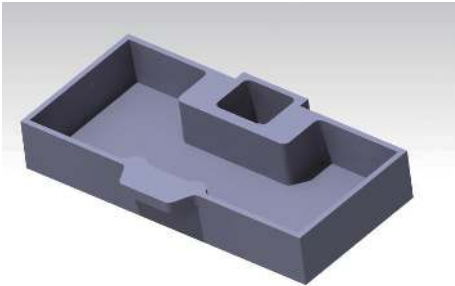
Fig. 16   CAD model of the sensor cover

model of the component was used for planning the fixture by automatically recognizing and extracting the features. The primary output window of the FiXplan software for the present case study does not show high level features like hole, boss, slot, hemispherical pocket, etc. However, they can be deduced based on logic mentioned in Section 2.2. These features, if required, can be incorporated in subsequent output windows after integrating the logic and developing a full-fledged feature extraction module in the program. The output window of the FiXplan software is presented in Fig. 17. The finishing operation was performed on the sensor cover, which is a cast aluminium alloy (LM 6) of outer dimensions 280 mm× 160 mm×45 mm. The orientation of the workpiece for a single machining sequence is identified. For the part, the various features are extracted, and based on the machining surface, the locator surface and the clamping surfaces were identified using the FiXplan software. The different locator position configuration suggested by the software was used for performing the finish machining of the sensor cover.

Experiments were conducted on a four-axis CNC vertical machining center (AGNI BMV 45 TC24) to validate the suggested locator position for the sensor cover. For the various locator configurations, finishing operations were conducted on the sensor cover. An end mill cutter of 16 mm diameter is rotated at 1 000 rpm, with a feed and depth of cut of 50 mm/min and 0.3 mm, respectively. In order to vindicate the required location configurations, a specially designed fixture is used for machining, as shown in Fig. 18.

The locator and clamping surfaces are identified from
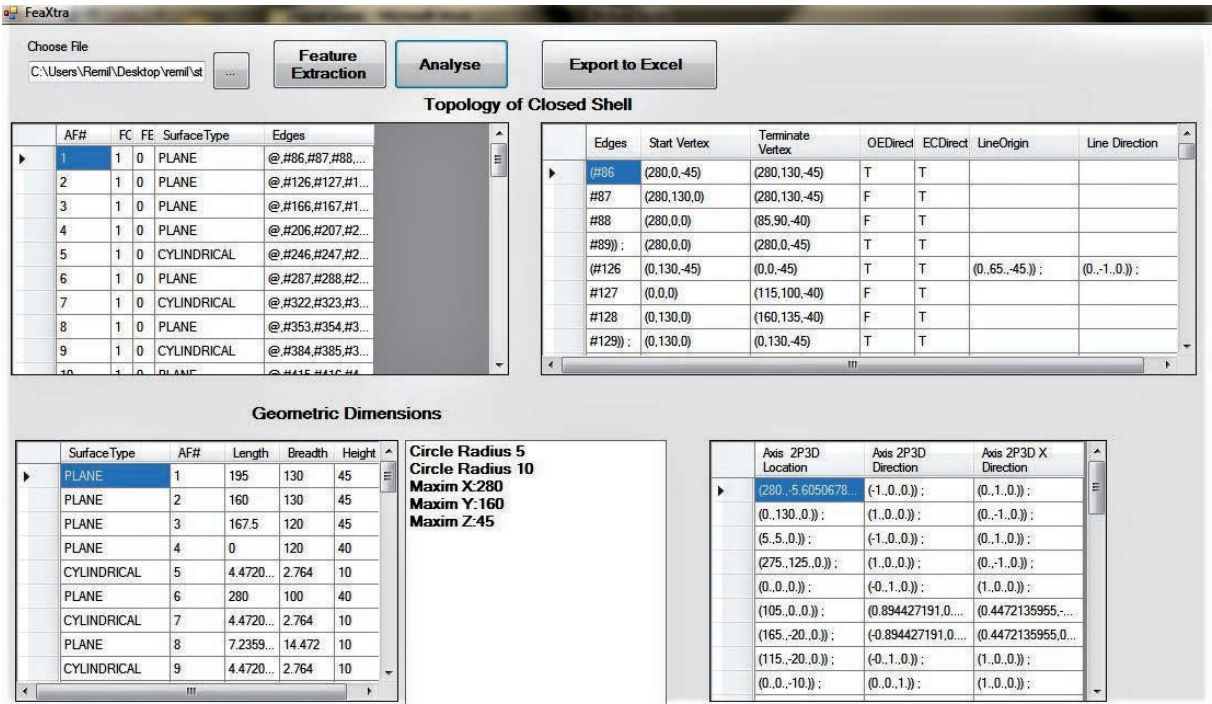

Fig. 17   Extracted feature data from FiXplan software

Fig. 18　Finish machining on the sensor cover mounted on the fixture

the FiXplan software for a particular machining sequence. The machined surfaces obtained by varying the locator configurations on the fixture are then characterized by measuring their areal surface roughness (Sa) and waviness in a 3D non-contact optical profilometer (Alicona infinite focus G5) as mentioned in Section 4. An area of $30 \, \text{mm} \times 5 \, \text{mm}$ was taken for the measurement of areal surface roughness (Sa) and waviness and the measurement results are presented in Table 4.

Table 4　Experimental observations during the machining of the sensor cover

Sl No.	Configuration	Areal surface roughness (μm)	Waviness (μm)
1	$L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50%	**1.331 5**	**0.275 0**
2	$L_1L_2L_3$ @ 15%; L_4L_5@ 15%; L_6@ 50%	1.669 8	0.320 8
3	$L_1L_2L_3$ @ 20%; L_4L_5@ 20%; L_6@ 50%	1.725 8	0.480 0
4	$L_1L_2L_3$ @ 30%; L_4L_5@ 30%; L_6@ 50%	2.260 4	0.572 2
5	$L_1L_2L_3$ @ 5%; L_4L_5@ 5%; L_6@ 50%	1.709 8	0.499 4

From the results obtained, it could be observed that the best surface characteristics were achieved for the locator position of 10% of the length of the specimen, which further validates the proposed locator configuration. Thus, the experimental results indicated that the ideal locator configuration for obtaining best surface characteristics is $L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50% dimensions of the primary, secondary and tertiary face for the prismatic part.

6　Conclusions

An approach has been presented through this paper to automate the fixture planning by suggesting primary, secondary and tertiary locating surfaces for a prismatic work piece, using the data extracted from a STEP AP 242 file of the CAD model of parts. The results of the FEM based numerical simulation indicated the minimal part deflec-

tion for a locator configuration of $L_1L_2L_3$ @ 10%; L_4L_5@ 10%; L_6@ 50% of the primary, secondary and tertiary face size of the prismatic part that uses 3-2-1 based fixture planning. Base locator enclosed area (%)/Workpiece base area (%) for this optimum configuration was observed to be 33%. Further, the combination of the locator configuration was found to be ideal for getting the best surface characteristics (minimum 3D roughness and waviness) on the part surface based on experiments conducted using a specially designed fixture with the provision for varying locator position. FiXplan software was developed for automatic feature recognition and to suggest the locator and clamping positions based on the extracted geometric dimensions and topology of the parts. To demonstrate the capability of the proposed approach, the finish machining of a sensor cover was presented as a case study that used the fixture planning scheme suggested by FiXplan software, and the proposed ideal locator configuration was experimentally verified. The proposed approach, generic in nature, can be suitably modified and adapted for the automation of fixture planning by extracting the features of the designed part from STEP AP 242 files of the part CAD models.

Acknowledgments

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