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DESIGN AND OPTIMIZATION OF MODULAR FIXTURE USING FINITE ELEMENT METHOD FOR CYLINDRICAL PARTS

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To ensure the production of high-quality parts, a precise fixture is essential in minimizing the workpiece displacement while maintaining positional accuracy, stability, and avoiding interference with the cutting tool. Workpiece deformation during machining operations can be curtailed by adequate selection, number, and position of locators/clamps. This work integrates advanced finite element method (FEM) simulations to accurately predict and optimize the performance of modular fixtures, improving precision, flexibility, and efficiency of the manufacturing process. An optimized fixture layout design methodology is proposed, enabling attainment of these machining objectives for quality work on solid and thin-walled cylindrical parts. In addition to geometric optimization, clamping forces are refined using the force-moment method, minimizing workpiece deformation and improving hold accuracy. The optimal layout is determined with minimal sample runs and implemented for drilling 14.5 mm diameter holes in Al-T3 pipes used in the HVAC systems of SANPAK Pvt. Ltd. The experimental results obtained after the modular fixture optimization through FEM were found to increase the accuracy of hole (rejection rate drop from 5% to 2%) and reduction in setup time and efficiency of process. A chi-square test confirmed the significance of this improvement ($\chi^2 = 20.05$, $p < 0.00001$). The unique study integrates multiple parameters, such as clamping force, deformation, and stability, in a single framework, for a comprehensive and improved solution to the challenges of fixture design for cylindrical parts. This approach enhances the overall effectiveness, adaptability, and cost of modular fixture design and provides manufacturing solutions applicable to diverse industrial components.

Keywords: Fixture Layout, Clamping Force, Harmonic Analysis, Optimization, Finite Element Analysis

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1. INTRODUCTION

From machining to assembly, nearly every manufacturing process relies on fixtures—work-holding devices that ensure minimal displacement and precise positioning of the workpiece. In production assembly lines, machining fixtures are essential for maintaining the workpiece in a fixed position and orientation throughout the machining process, effectively countering machining forces. The key requirements for an effective machining fixture include high positioning accuracy, adequate support, minimal displacement and deformation, and no interference with the cutting tool (Vasundara and Padmanaban, 2014).

The workpiece must be completely constrained in order to obtain precision and work quality during the machining processes. The workpiece location and fixture layout have a major impact on the product performance in the domains of component precision and dimensional accuracy. Workpiece deformation throughout machining processes must be reduced by carefully selecting the number, position of locating pins and clamps (Vasundara *et al.*, 2012).

In the specialized literature, various researchers have optimized the multiple parameters of fixtures for better performance during the machining and assembly operations. In a feature-based approach, some authors described how to decide overall fixture properties depending on the features associated with machining and the design restrictions (Subrahmanyam, 2002). Moreover, empirical relations were presented to identify the design parameters, and the fixing features, such as supporting, locating, along with clamping positions. Amaral *et al.* (2005) developed a technique to

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control the workpiece boundary parameters and external forces applied throughout machining. They investigated the flexible fixture tool contact deviation region and automatically optimized support placements using finite element analysis (FEA).

Nonlinear FEA optimization techniques combined with GA & artificial neural networks (ANN) have also been exploited for fixture placement in machining operations. The workpiece's maximum deformation was computed with ANN, and the ideal clamping forces were found by GA (Hamedi, 2005; Aoyama *et al.*, 2006). Another researcher used balancing force moment equations to determine clamping forces and locator reaction forces. The authors then analyzed the deformation of the workpiece for different locations of locators using FEA (Zheng *et al.*, 2008). Padmanaban *et al.* (2009) exploited a genetic algorithm (GA) and an ant colony algorithm (ACA) for the fixture layout optimization approach. On the same geometry of the workpiece, three different node systems were built to verify the dependability of the GA and ACA performances. Wang, Rong *et al.* (2010) examined spring-gap elements with stiffness, separation, and friction characteristics to model elastic workpiece boundary properties. Selvakumar *et al.* (2013) used ANN and DOE methods to find the solution region with maximum elastic deformation. They found that ANN is the best suited for finding solution regions with multiple fixture layout parameters. Sundararaman *et al.* (2014) used sequential approximation optimization (SAO) and LINGO solver to optimize the deformation for optimal locators and clamps position. Xing (2017) proposed a fully automated method for fixture layout optimization, combining 3DCS simulation and global optimization algorithms. The method reduced computational effort by filtering candidate locating points and automating the optimization process using MATLAB.

The traditional assembly of aircraft panels relied on special welding fixtures, which were inefficient for the timely production of diverse products. To address this, Meng *et al.* (2023) designed a low-cost reconfigurable flexible fixture for preassembling panels (RFFP), aiming to optimize the fixture layout for aerodynamic accuracy. They proposed an intelligent optimization method combining convolutional neural networks (CNN) and genetic algorithms (GA) to minimize strain energy and improve assembly quality. Celek *et al.* (2023) designed a flexible modular fixture for aircraft fuselage panel assembly. Another researcher proposed a concept for locating complex-shaped parts. They analyzed the stress and deflection of steering knuckle elements using finite element modeling, and static loading experiments validated the results (Kolesnyk *et al.*, 2024). The following table further summarizes a few key research findings related to fixture design and optimization in comparison with the current research.

Table 1. Comparative summary of key literature on fixture design and optimization alongside current study outcomes

Author(s)	Method Used	Objective	Component Type	Key Findings
Siebenaler and Melkote (2006)	Finite Element Analysis	Analyze fixture–workpiece deformation and surface errors	Fixture elements & workpieces	Predicted deflection errors; evaluated deformation distributions
Deng and Melkote (2006)	Clamping Force Analysis	Ensure stable clamping force during machining	Work holding systems	Identified required clamping forces for secure part stabilization
Qin, Zhang *et al.* (2006)	Clamping Force Maximization	Reduce positioning errors during machining	General	Improved accuracy by maximizing clamp force
Chen, Ni *et al.* (2008)	Multi-objective Optimization	Minimize surface deformation considering chip removal/friction	Machined Surface	Optimization reduced deformation via multi-factor modeling
Dong *et al.* (2016)	Static + Dynamic FEA	Minimize surface error through material removal/load analysis	Thin-Walled Component	Found ideal locator triangle, reduced deformation across 10 load steps
Möhring and Wiederkehr (2016)	Process Simulation + Sensors/Actuators	Analyze fixture impact on machining accuracy	General	Linked advanced sensors/actuators to fixture design for performance improvement
Calabrese *et al.* (2017)	Topology Optimization	Optimize fixture for thin-walled cylindrical parts	Cylindrical Part	Used a solid lattice model to achieve fixture stiffness with less material
Ivanov *et al.* (2019)	ANSYS Simulation (Modal Analysis)	Model fixture–workpiece vibration behavior	Fork-Type CNC Parts	Dynamic stability
Pawar *et al.* (2024)	Finite Element Analysis (Slot Milling)	Model force vs. stress impact on fixture system	Workpiece-Fixture Assembly	Optimized clamping force to reduce von Mises stress and part deflection

Author(s)	Method Used	Objective	Component Type	Key Findings
Cioată *et al.* (2018)	Modular Fixture Stiffness Analysis	Evaluate the influence of joints and friction	Modular Fixture Orientation System	Identified key stiffness parameters under varying joint configurations
Michael Thomas Rex *et al.* (2021)	PFEM + Genetic Algorithm	Optimize layout for flexible fixtures	Prismatic Parts (Pocket Milling)	Reduced search space and improved deformation control
Ivanov *et al.* (2022)	Numerical Simulation	Design an efficient fixture for connecting rods	One-Piece Connecting Rods	Reduced vibration, improved machining accuracy, and reduced tooling
Present Work	Force-Moment + FEA + Empirical Study	Reduce deformation, rejection, and setup time in real parts	Solid cylindrical part and thin tube (Al 2024-T3)	31% lower deformation, 44% less setup time, 3% drop in rejection; validated onsite

The novelty of this study lies in its innovative approach to designing and optimizing modular fixtures for solid and thin-walled cylindrical parts using the finite element method (FEM). While previous research works have focused on maximizing fixture configuration to minimize peripheral workpiece distortion, this work integrates advanced FEM simulations to accurately predict and optimize the performance of modular fixtures, improving the precision, flexibility, and efficiency of the manufacturing process. By considering multiple parameters such as clamping force, deformation, and stability in a single framework, this research provides a comprehensive solution to the challenges of fixture design for cylindrical parts used in the automotive part manufacturing sector, offering significant improvements over conventional methods. This approach not only enhances the overall effectiveness of modular fixtures but also paves the way for more adaptable and cost-efficient manufacturing solutions in diverse industrial applications.

2. METHODOLOGY

The proposed methodology begins with the development of a CAD model of the selected cylindrical workpiece using SolidWorks. Appropriate fixture elements, including V-Blocks, stoppers, and clamps, were chosen from a graphical database of modular fixture components. The fixture workpiece assembly was then constructed following the 3-2-1 locating principle to ensure stability and proper constraint during the machining process.

Once the model was assembled, it was exported in Parasolid format from SolidWorks and imported into ANSYS Workbench for simulation. During the pre-processing phase, the material properties for both the workpiece and fixture components were defined. The geometry was discretized using a mesh with a refinement level of 3 to ensure sufficient accuracy in the finite element analysis. Boundary conditions were applied at the specified positions of the locators, stoppers, and clamps, reflecting real-world constraints. To ensure the workpiece remained stable during machining:

- Machining and clamping forces were calculated and applied based on the selected machining feature.
- The fixture layout was optimized using the Finite Element Method (FEM) to minimize distortion in the workpiece.

In addition to fixture layout optimization, the analysis also accounted for the influence of material removal during the machining process. This was achieved by segmenting the tool path into discrete load steps, with each step representing a specific position of the cutting tool. At each load step, a force-moment matrix was formulated based on the fixture setup and machining forces. This matrix was solved in MATLAB to determine the optimal clamping forces required to maintain part stability while minimizing distortion. Once the optimal forces were identified, they were reapplied in ANSYS simulations to evaluate the corresponding workpiece deformation. This integrated approach, combining CAD modeling, FEM analysis, and MATLAB-based force optimization, provided a comprehensive framework for designing a robust and efficient modular fixture for cylindrical parts (Mughal *et al.*, 2023).

2.1. Geometric Modeling of Fixture and Workpiece

The solid cylindrical-shaped workpiece was developed using a CAD software package (SolidWorks). The fixture elements, like V-Block and stoppers, were imported and assembled to obtain the fixture workpiece model. The developed model is presented in Figure 1. In the current analysis, the workpiece material was taken to be homogeneous, isotropic, and linear elastic. Fixture body material was selected as alloy steel 4140. The mechanical properties of selected workpiece and fixture elements are listed in Table 2.

The machining operation performed on the cylindrical workpiece rod is drilling. To determine both the magnitude and direction of the machining forces required for the analysis, force and moment components were modeled. The total force F acting on the two lips of the drill bit is resolved into three orthogonal components (Wang *et al.*, 2025), as illustrated in Figure 2.

- The thrust force (F_a) along the drill's axis, due to the downward push for the drilling operation.
- The drill bit's lateral force in the direction of action of the radial force (F_r).
- Force (F_t), tangent to force components F_a and F_r (Chou, 1994)

When the radial forces (F_r) on each drill lip are equal and opposite, they cancel out, producing what is considered the optimal condition. However, the axial component F_a acts simultaneously on both lips, resulting in a net axial thrust (P) on the workpiece. Meanwhile, the tangential components F_t generate a torque (M) that resists the rotation of the drill. As the drill penetrates the workpiece, the cutting forces initially increase, then stabilize once the tool reaches a steady state cutting condition. For the purposes of this study, these forces were considered under steady-state conditions to simplify the numerical simulation and ensure computational efficiency (Mannan and Sollie, 1997; Krishnakumar and Melkote, 2000).

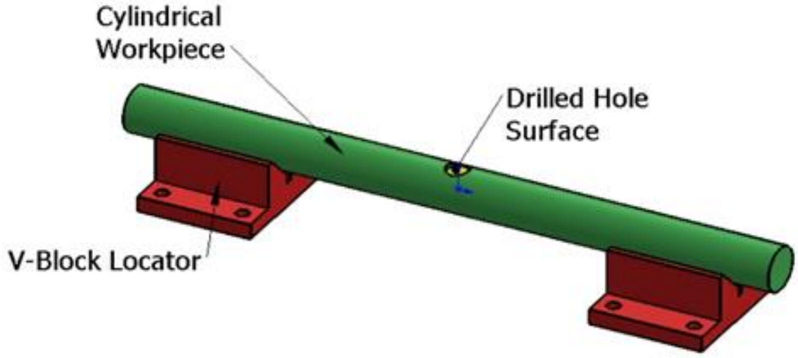


Figure 1. Fixture-Workpiece Model with Drilled Hole

Table 2. Mechanical properties of materials used for fixture and workpiece

Property	Al 2024-T3	4140 Steel
Young's Modulus (E)	73.1 GPa	210 GPa
Density (ρ)	2780 kg/m^3	7850 kg/m^3
Poisson's Ratio (ν)	0.33	0.3

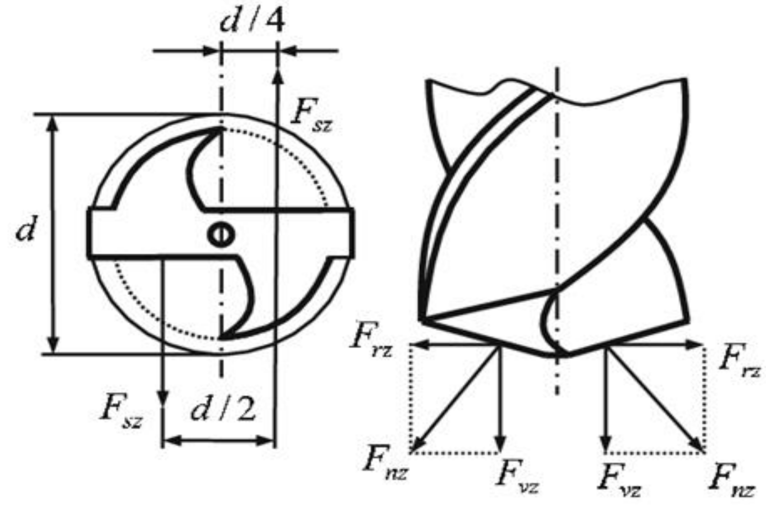


Figure 2. Force components in drilling

For cutter diameter D (mm), rake angle k (rad), advance in one revolution of the spindle a (mm/rev), number of flutes of cutter N_f and material hardness h, the chip thickness h_{avg} (mm), tangential force P_x (N), thrust force P_z (N) and drilling torque M_p (Nm) can be calculated as follows.

$$h_{avg} = [a \times \cos(k/2)/N_f] \tag{1}$$

$$P_x = M_P \times D/2 \tag{2}$$

$$P_z = 4.6343 \times D0.97 \times h_{avg} \times 0.83 \times h \times 0.5 \tag{3}$$

$$M_p = 0.001542 \times D \times 2.0 \times h_{avg} \times 0.8 \times h \times 0.5 \tag{4}$$

Based on these parameters, the drilling forces, i.e., tangential, radial, and normal machining forces, were calculated and listed in Table 3. The drilling tool position is discretized into five load steps for the calculation of clamping forces at each step for a stable machining operation.

Table 3. Computed drilling forces and torque values based on cutter geometry

Parameter	**Value**
Types of Operation	Drilling
Cutter diameter	7 mm
Number of Flutes	2
Spindle Speed	2200 rpm
Feed	0.1 mm/rev
Rake Angle	30°
Hardness of the Workpiece	120 N/mm^2
Machining Force F_x	0 N
Machining Force F_y	621 N
Machining Force F_z	477 N
Drilling Torque	2.67 Nm

2.2. Computational Domain and Boundary Conditions

One essential FEA pre-processing step is to define the computational domain and discretize the geometric model. The accuracy and time required for the computational solution depend upon the refinement and orientation of the mesh (number of nodes and elements) [32]. In this work, mesh refinement level 3 is selected for free mesh generation, and Figure 3 indicates the computational domain and meshing of the fixture workpiece model.

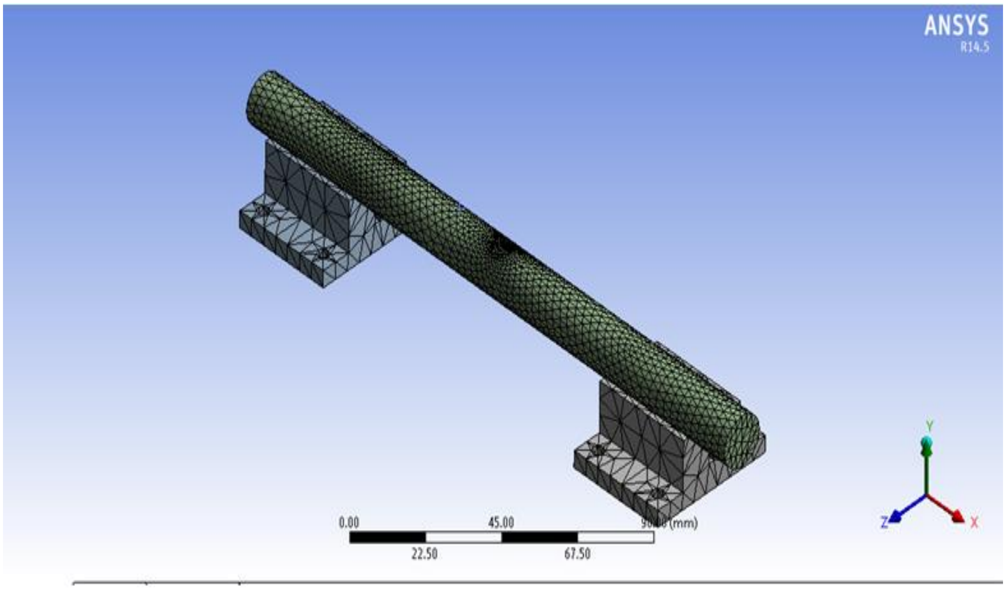
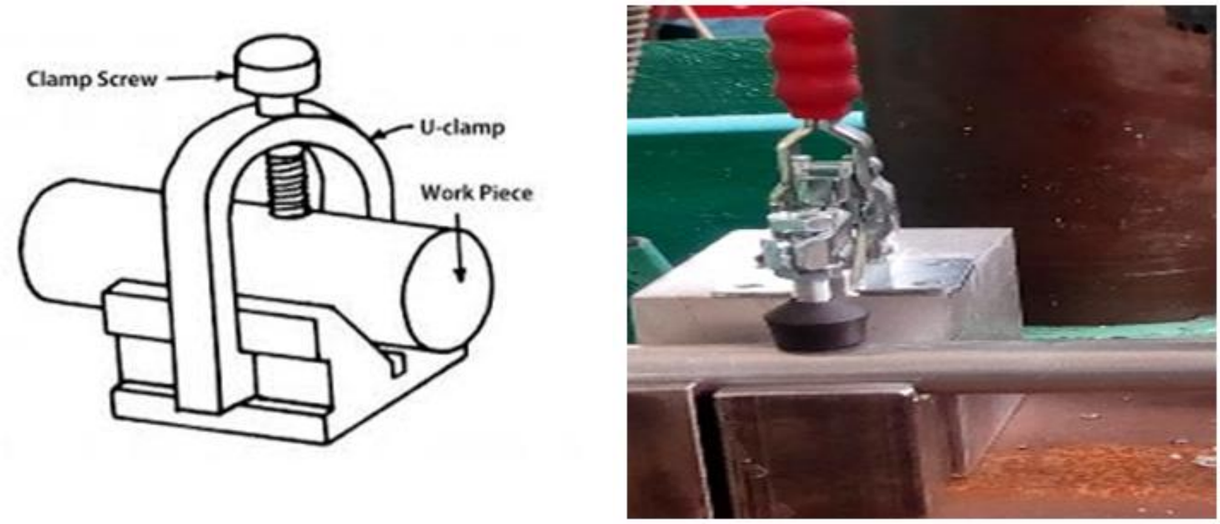


Figure 3. FEA mesh of the fixture-workpiece model

Clamps and locators define the boundary conditions of the workpiece model. Locators are used to restrain the movement of the workpiece during machining operations by preserving the position of the job in the fixture. V-Block locators for cylindrical parts act as point contacts normal to the workpiece. In the current model, the locators contact the Y-Z axis at an angle, and hence the reaction forces were divided into two components. To fulfill the 3-2-1 fixture layout principle, one locator is located at the end of the workpiece in the Z axis. Once the workpiece is secured in locators, then clamps are used to speed up the job process. Clamps can apply a variable or fixed clamping force. Different types of clamping mechanisms are used to apply force, i.e., hydraulic, pneumatic, or manual (Dong *et al.*, 2016). Usually, clamping forces are applied either by bolt mechanisms or toggle clamps in the industry to act as a point clamping force at the center of the circular or rectangular surface of the workpiece. Commonly used locators for cylindrical parts are V-Blocks, as shown in Figure 4.

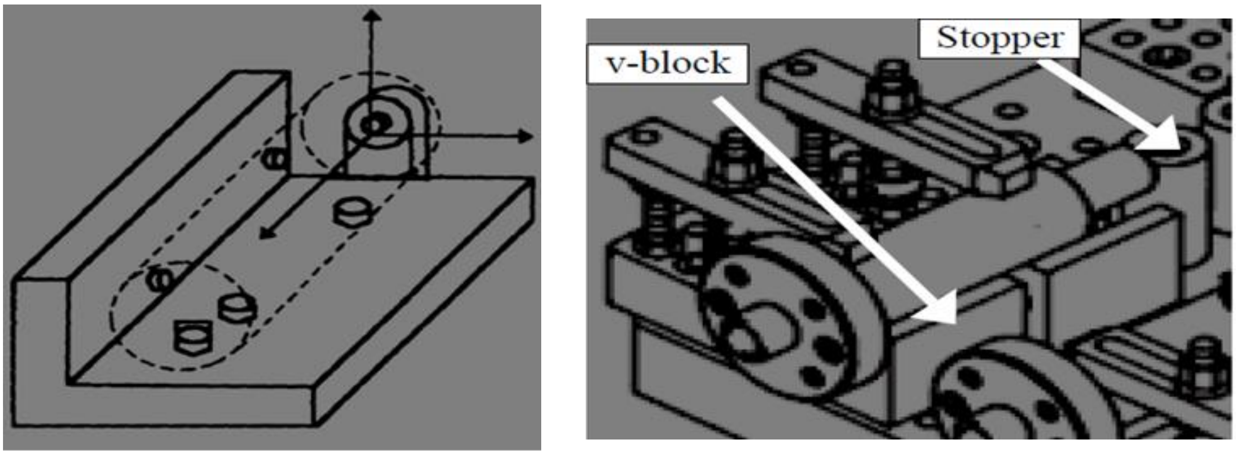


(a) V-Block with screw clamping arrangement (b) V-Block with toggle clamp arrangement

Figure 4. Locators and clamps arrangements for the cylindrical part

A workpiece mounted in a fixture inherently possesses six degrees of freedom (DOF), or twelve if both positive and negative motions along each axis are considered separately, as suggested by some researchers. An effective fixture layout is designed to systematically constrain these degrees of freedom during machining, ensuring the workpiece is accurately positioned and securely held relative to the cutting tool.

Figure 5a demonstrates how the cylindrical workpiece is located using the 3-2-1 locating principle. In Figure 5b, a V-Block is shown as the primary locator for cylindrical parts. The V-Block restricted 4 degrees of freedom motion (linear motions along X and Z directions, rotation about X and Z axis), the stopper restricted the linear motion along Y direction, while the 6th degree of freedom is not required to be restricted because of the part symmetry about the Y axis.



(a) 3-2-1 Locating principle for cylindrical parts (b) V-Block is used to achieve this principle for cylindrical parts

Figure 5. 3-2-1 Fixture layout for cylindrical part in ANSYS (Sundararaman *et al.*, 2014)

Figure 6 illustrates the implementation of the 3-2-1 locating principle within the ANSYS Workbench environment for the fixture–workpiece system. In this setup, the V-Block serves to restrict one face of the cylindrical workpiece, effectively acting as a stopper. Clamping forces are applied using remote point loads directed vertically downward to simulate realistic holding conditions. The complete set of boundary conditions, applied in accordance with the fixture layout, is depicted in Figure 7, showing how the cylindrical rod is constrained during simulation in ANSYS.

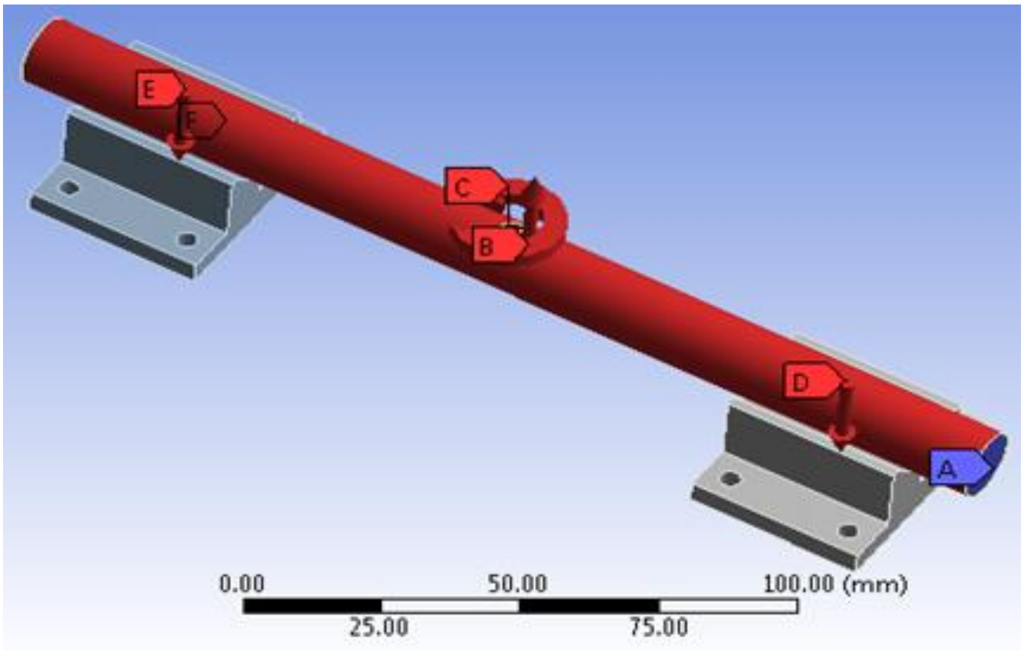


Figure 6. Boundary condition setup using the 3-2-1 principle

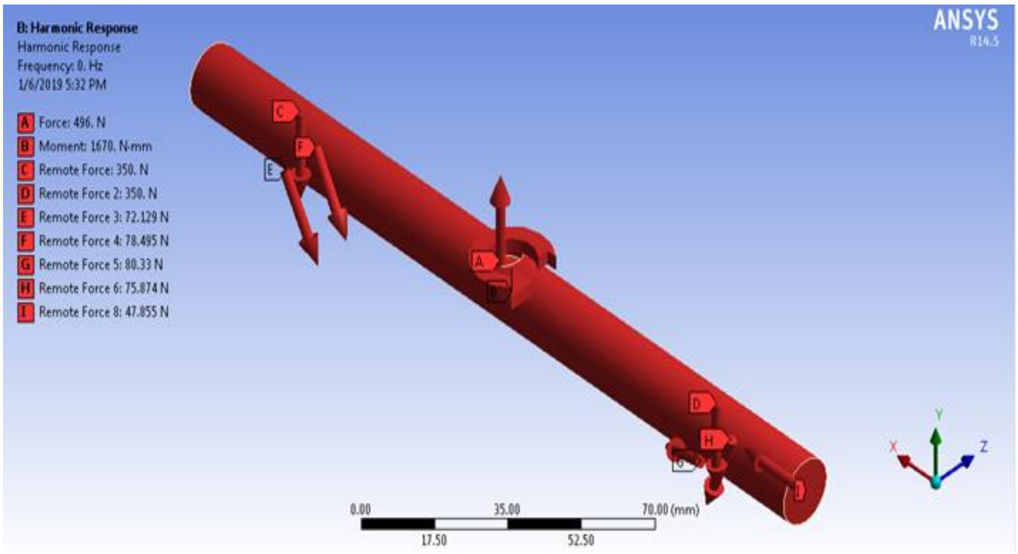


Figure 7. Harmonic response analysis of fixture layout in ANSYS

2.3. Fixture Layout Optimization

The step-by-step methodology for optimizing the fixture workpiece layout is presented in Figure 8. Initially, the assembled fixture–workpiece model created in SolidWorks is imported into ANSYS Workbench for harmonic analysis. Once imported, material properties for both the workpiece and the fixture components are assigned. Subsequently, boundary conditions, including the positions and limits of fixture elements, are applied to the model. The simulation is then executed to evaluate reaction forces and deformation along the cylindrical workpiece at various points. This methodology is designed to determine the most effective fixture layout for drilling operations on cylindrical parts, using finite element analysis (FEM) in ANSYS to achieve minimal deformation and enhanced stability during machining.

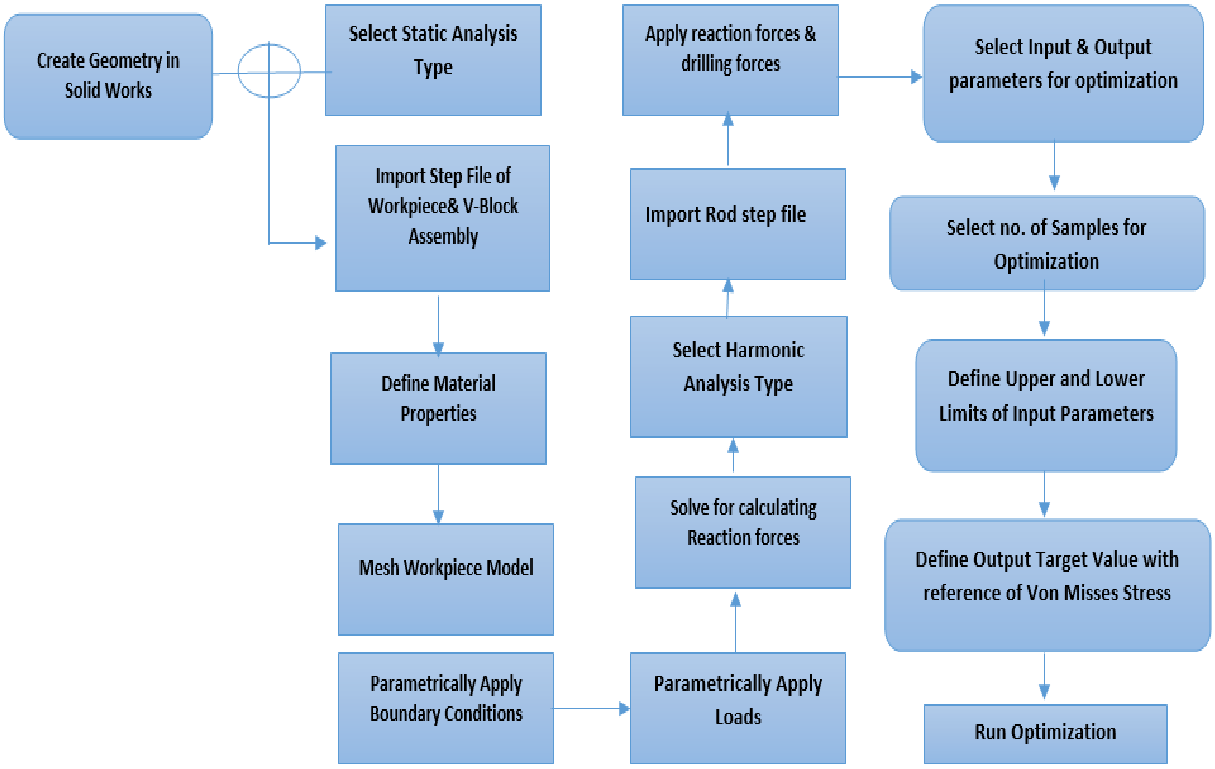


Figure 8. Workflow for fixture layout optimization

The following parameters affect the deformation of the workpiece (Boyle *et al.*, 2011)

- Materials of the fixture parts
- Materials of the workpiece
- Locating locators, clamps, and supports
- Number of clamps, their forces & location sequence

The minimum clamping forces required to securely hold the workpiece during the application of machining, clamping, and locating forces were selected for analysis. Optimizing both the clamping forces and the overall fixture layout is essential to minimizing deformation in the workpiece during drilling operations. The key parameters used in optimizing the process were categorized as design variables, state variables, and output (objective) variables, as listed in Table 4.

Table 4. Fixture layout optimization variables

Design Variables	Position of Locators V Block 1 ($X1$, $Y1$, $Z1$) V Block 1 ($X1$, $Y1$, $Z2$) V Block 2 ($X2$, $Y2$, $Z3$) V Block 1 ($X2$, $Y2$, $Z4$) Position of Clamps Clamp 1 ($X1$, $Y1$, $Z1$) Clamp 2 ($X2$, $Y2$, $Z2$) Stopper (Fixed) Stopper 1 ($X1$, $Y1$, $Z1$)
State Variables	Von Misses Stress (VONMISES< Yield Strength)

Objective Function: Maximum Displacement	DMAX

Lower and upper limits for clamps and locators were selected based on the safe working region. Lower limit selected by considering the drilling chuck diameter and V-Block center to end clearance, i.e., (17.5 mm distance from the center of V-Block to end distance). Similarly, the upper limit (85 mm) is selected based on the V-Block dimension to provide enough support for the workpiece. Table 5 shows the lower and upper limits of fixture elements.

Table 5. Positional limits of clamps, stoppers, and locators for safe and effective fixture layout optimization.

Variable Name	**Lower Limit (mm)**			**Upper Limit (mm)**		
	X	**Y**	**Z**	**X**	**Y**	**Z**
L_1	5.1	−5.1	40	5.1	−5.1	85
L_2	−5.1	−5.1	40	−5.1	−5.1	85
L_3	5.1	−5.1	−40	5.1	−5.1	−85
L_4	−5.1	−5.1	−40	−5.1	−5.1	−85
L_5	0	0	−100	0	0	−100
C_1	0	7.25	40	0	7.25	85
C_2	0	7.25	−40	0	7.25	−85

2.4. Clamping Forces Optimization

Initially, sufficient clamping forces were applied in the fixture layout to ensure the workpiece remained stable during the machining process. However, once the fixture layout was optimized, it became necessary to further refine the clamping forces to minimize workpiece deformation and enhance overall stability. The force moment matrix was developed from free body shear moment diagram of cylindrical rods illustrated in Figure 9, at which Y_1 & Y_2 point shows the clamping point. L_{11}, L_{12}, L_{21} and L_{22} are locators point while point 3 showing stopper point. This matrix was solved in MATLAB to optimize the clamping forces.

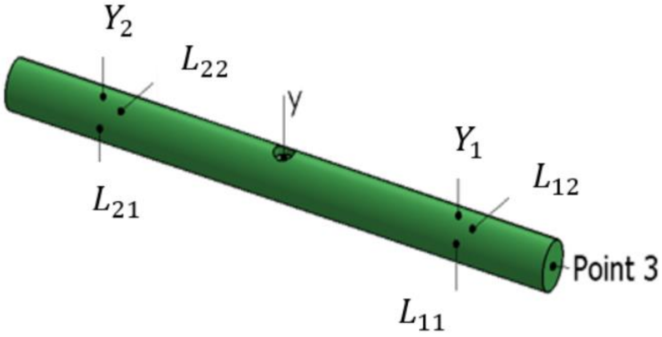


Figure 9. Locator and clamp points used in force analysis

Clamping forces optimization analysis performed by dividing the entire tool path into five discretized load steps to consider material removal effect during analysis. The reaction forces at the locator and Stopper points are denoted by $R_{x_{11}}$, $R_{x_{12}}$, $R_{x_{21}}$, $R_{x_{22}}$, $R_{y_{11}}$, $R_{y_{12}}$, $R_{y_{21}}$, $R_{y_{22}}$, R_{y_3} and R_z. The clamping forces are denoted by R_{y_1} and R_{y_2} at respective points. The force moment matrix is developed as follows.

$$\sum F_x = 0, \quad \sum F_y = 0, \quad \sum F_z = 0$$
$$\sum M_{y_1} = 0, \quad \sum M_{L_{11}} = 0, \quad \sum M_{L_{12}} = 0$$
$$\sum M_{y_2} = 0, \quad \sum M_{L_{21}} = 0, \quad \sum M_{L_{22}} = 0$$
$$\sum M_{y_3} = 0, \quad \sum M_{L_3} = 0, \quad \sum M_3 = 0$$

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{y_1} \\ M_{y_2} \\ M_{y_3} \\ M_3 \\ M_{11} \\ M_{12} \\ M_{21} \\ M_{22} \\ M_y \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} & a_{19} & a_{110} & a_{111} & a_{112} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} & a_{28} & a_{29} & a_{210} & a_{211} & a_{212} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & a_{37} & a_{38} & a_{39} & a_{310} & a_{311} & a_{312} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & a_{47} & a_{48} & a_{49} & a_{410} & a_{411} & a_{412} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} & a_{57} & a_{58} & a_{59} & a_{510} & a_{511} & a_{512} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & a_{67} & a_{68} & a_{69} & a_{610} & a_{611} & a_{612} \\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & a_{77} & a_{78} & a_{79} & a_{710} & a_{711} & a_{712} \\ a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & a_{86} & a_{87} & a_{88} & a_{89} & a_{810} & a_{811} & a_{812} \\ a_{91} & a_{92} & a_{93} & a_{94} & a_{95} & a_{96} & a_{97} & a_{98} & a_{99} & a_{910} & a_{911} & a_{912} \\ a_{101} & a_{102} & a_{103} & a_{104} & a_{105} & a_{106} & a_{107} & a_{108} & a_{109} & a_{1010} & a_{1011} & a_{1012} \\ a_{111} & a_{112} & a_{113} & a_{114} & a_{115} & a_{116} & a_{117} & a_{118} & a_{119} & a_{1110} & a_{1111} & a_{1112} \\ a_{121} & a_{122} & a_{123} & a_{124} & a_{125} & a_{126} & a_{127} & a_{128} & a_{129} & a_{1210} & a_{1211} & a_{1212} \end{bmatrix} \begin{bmatrix} X_{11} \\ X_{12} \\ X_{21} \\ X_{22} \\ Y_1 \\ Y_2 \\ Y_3 \\ Y_{11} \\ Y_{12} \\ Y_{21} \\ Y_{22} \\ Z_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The above matrix is solved by using MATLAB at each load step to calculate clamping forces at various tool positions. The calculated clamping forces at different load steps are given in Table 6.

Table 6. Clamping force values calculated at different load steps

Load Step	Clamping Force C_1 (N)	Clamping Force C_2 (N)
1	-695.4	-120.2
2	-695.75	-117.14
3	-695.1	-114.12
4	-696.4	-111.1
5	-696.73	-108.1

Optimized clamping forces are: $C_1 = 696.73$, $C_2 = -120.2$. The steps involved in the optimization of clamping forces are shown in Figure 10.

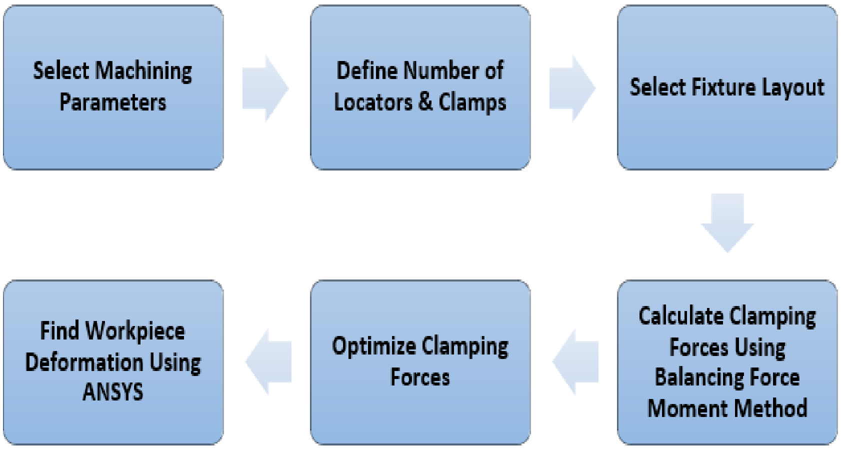


Figure 10. Clamping forces optimization process

Based on the selected drill size and workpiece material, the machining forces were initially calculated. Next, the most suitable fixture configuration was determined by considering the type and number of fixture elements. The fixture workpiece system was then analyzed across multiple load steps by applying the optimized clamping forces.

In the first load step, the tool penetrated the workpiece to a depth of 1.5 mm. By the 5th load step, the tool had reached a depth of 7.5 mm, indicating progressive material removal. The analysis revealed that workpiece deformation is largely influenced by the extent of material removed during the machining process. At each load step, harmonic analysis was used to evaluate and optimize the fixture workpiece system to determine the corresponding maximum workpiece deformation. Figure 11 shows the maximum workpiece deformation at the final load step.

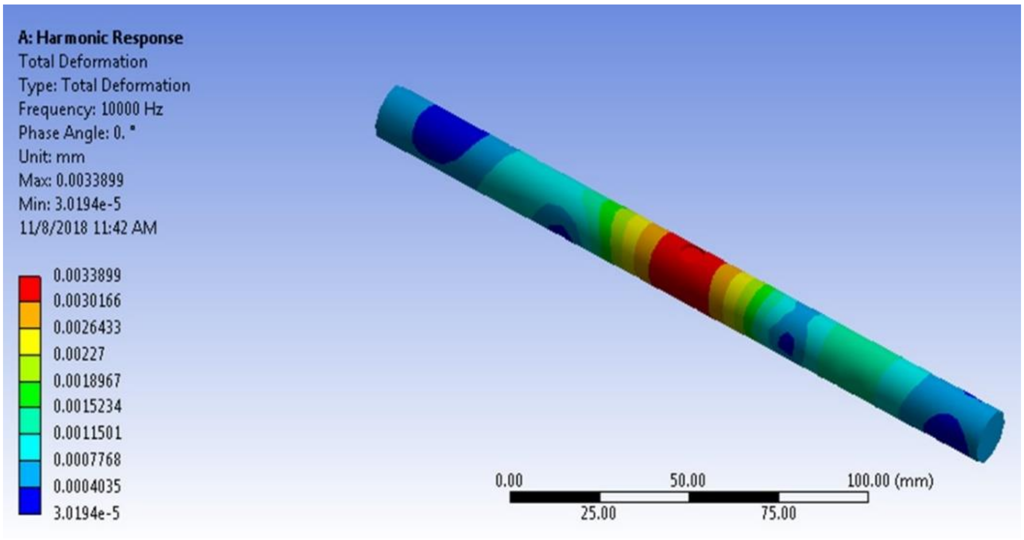


Figure 11. Deformation contours at different load steps

2.5. Optimized Fixture Layout Scheme/configuration

Suitable fixture layout scheme determines the workpiece deformation during the machining process (Xu and Wang, 2023). The significance of the fixture layout can be analyzed from workpiece deformation under both initial and optimized fixture layout conditions. An optimal fixture layout was identified using ANSYS through iterative analysis of 15 sample configurations. The ANSYS optimizer evaluated these samples and selected the most suitable layouts based on minimized workpiece deformation. The outcomes of this optimization process are presented graphically in Figure 12.

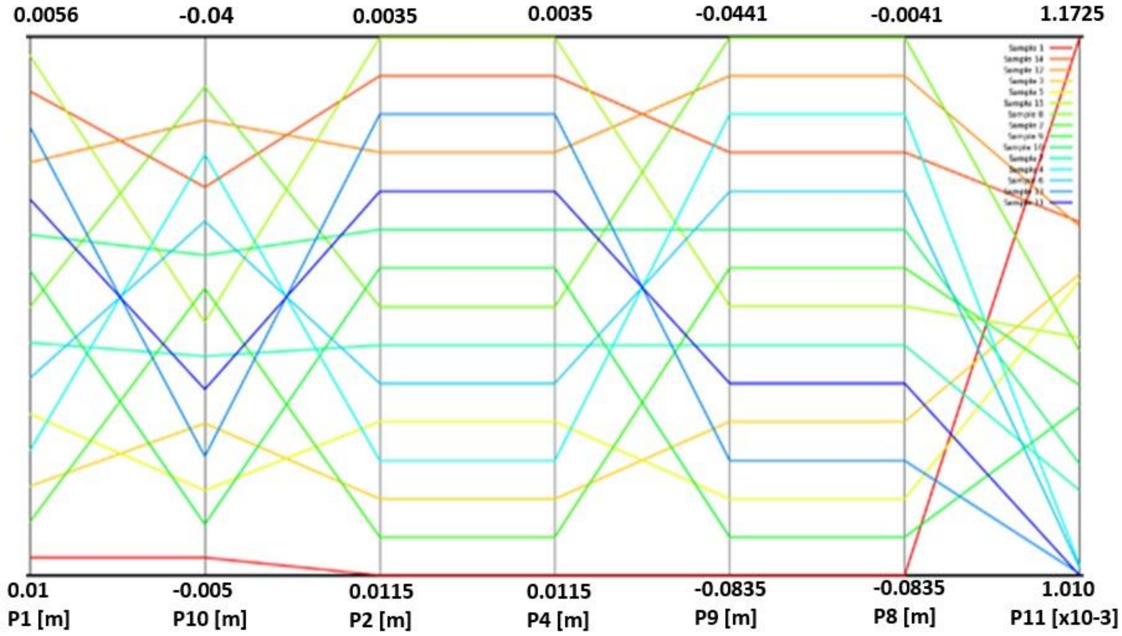


Figure 12. Deformation response of 15 fixture layout samples

From the 15 analyzed samples, ANSYS identified the three fixture layouts that show minimum workpiece deformation within the defined variable limits. This most suitable combination of parameters is shown in Figure 13.

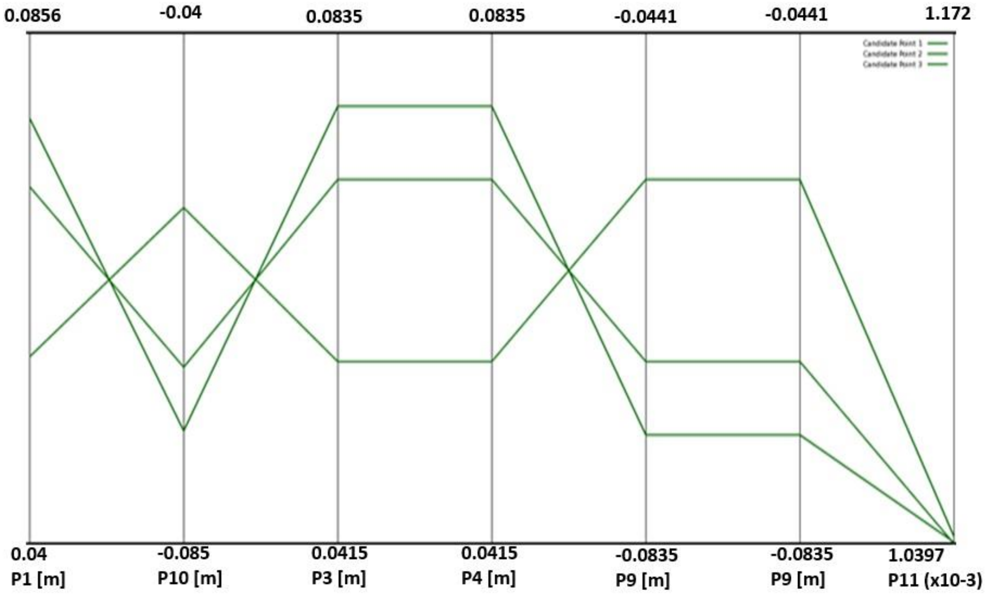


Figure 13. Top 3 optimized fixture layouts with minimum deformation

The initial arrangement served as a basis for the comparison of the amount of deformation reduced during the optimization process, as well as to stabilize the fixture workpiece system. Table 7 compares the initial and optimized fixture arrangements. Workpiece deformation for initial, optimized fixture layout, and clamping force scenarios are presented in Table 8 at each load step. The results demonstrate a noticeable reduction in workpiece deformation, achieved through the optimization of both the fixture layout and clamping force parameters compared to the initial setup.

Table 7. Comparison of initial and optimized positions of clamps and locators

Variable Name	**Initial Configuration (mm)**			**Optimized Configuration (mm)**		
	X	**Y**	**Z**	**X**	**Y**	**Z**
L_1	5.1	−5.1	75	5.1	−5.1	59.5
L_2	−5.1	−5.1	75	−5.1	−5.1	59.5
L_3	5.1	−5.1	−75	5.1	−5.1	−66.6
L_4	−5.1	−5.1	−75	−5.1	−5.1	−66.6
L_5	0	0	−100	0	0	−100
C_1	0	7.25	75	0	7.25	59.5
C_2	0	7.25	−75	0	7.25	−66.6

Table 8. Workpiece deformation values at multiple load steps for initial, optimized fixture layout, and clamping force scenarios

"Scenario	**Deformation Value (mm)**
Load Step 1	0.0134
Load Step 2	0.0104
Load Step 3	0.013
Load Step 4	0.015
Load Step 5	0.0136
Initial fixture layout	0.015
Optimized fixture layout	0.015
Optimized clamping forces	0.015

3. EXPERIMENTAL VERIFICATION / INDUSTRIAL CASE STUDY

The fixture workpiece assembly developed for cylindrical components in this study was validated through an industrial case study. An Al-T3 pipe with a diameter of 14.5 mm, used in an automobile HVAC system, served as the workpiece model. A hole needed to be drilled into the pipe for the installation of a refrigerant charging valve. This pipe is held firmly to counter all the machining forces. Two V-Block locators and a stopper in the tertiary plane were arranged in a 3-2-1 arrangement to hold the workpiece. Toggle clamps were placed vertically downward at the center of V-Blocks. Figure 14 illustrates the initial fixture arrangement with clamps, locators, and a stopper. Drilling forces were similar as described earlier, as the workpiece material and profile are similar. Dimensions of the pipe and machining forces are presented in Table 9.

In the first step, the CAD model was developed for the workpiece and fixture assembly. The developed assembly was then imported in para-solid format from SolidWorks to ANSYS Workbench. The model was discretized, and boundary conditions were defined based on the positions of locators, stoppers, and clamps. A numerical analysis was performed to evaluate workpiece deformation and stress distribution. Subsequently, the fixture configuration was optimized using the Finite Element Method (FEM) to minimize deformation of the part model during the machining process.

Figure 14. Initial fixture layout for Al-T3 pipe

Table 9. Dimensional specifications of Al-T3 pipe used in the experimental HVAC case study.

Parameter	Measurement
Outer diameter	$14.5\ mm$
Inner diameter	$10.5\ mm$
Wall thickness	$2\ mm$"
Machining forces	
F_x	$0\ N$
F_y	$621\ N$
F_z	$477\ N$
Drilling torque	$1.2\ Nm$

3.1. Fixture Layout Optimization

After analyzing the initial fixture layout, input (design) parameters were used for various optimization solutions. Lower and upper limits for clamps and locators were selected based on the safe working region. Lower limit selected by taking into consideration of the drilling chuck diameter and V-Block center to end clearance, i.e., 17.5mm distance from the center of the V-Block to the end distance. Similarly, the upper limit of $85\ mm$ was selected based on the V-Block dimension to provide enough support to the workpiece. Input parameter limits for optimization are given in Table 10.

Table 10 Upper and Lower Limits of Fixture Elements for Optimum Fixture Layout

Variable name	Lower limit (mm)			Upper limit (mm)		
	X	Y	Z	X	Y	Z
L_1	5.1	-5.1	40	5.1	-5.1	85
L_2	-5.1	-5.1	40	-5.1	-5.1	85
L_3	5.1	-5.1	-40	5.1	-5.1	-85
L_4	-5.1	-5.1	-40	-5.1	-5.1	-85
L_5	0	0	-100	0	0	-100
C_1	0	7.25	40	0	7.25	85
C_2	0	7.25	-40	0	7.25	-85

The selected optimization parameters—comprising 15 samples and a defined objective function—were applied for fixture layout optimization. Finite Element Analysis (FEA) identified three configurations that resulted in minimal workpiece deformation. Figures 15 and 16 illustrate the fixture layout optimization, comparing the initial fixture layout (IFL) with the optimized fixture layout (OFL). The results indicate significantly reduced workpiece distortion in the optimized arrangement. A comparative summary of the original and optimized fixture setups is provided in Table 11.

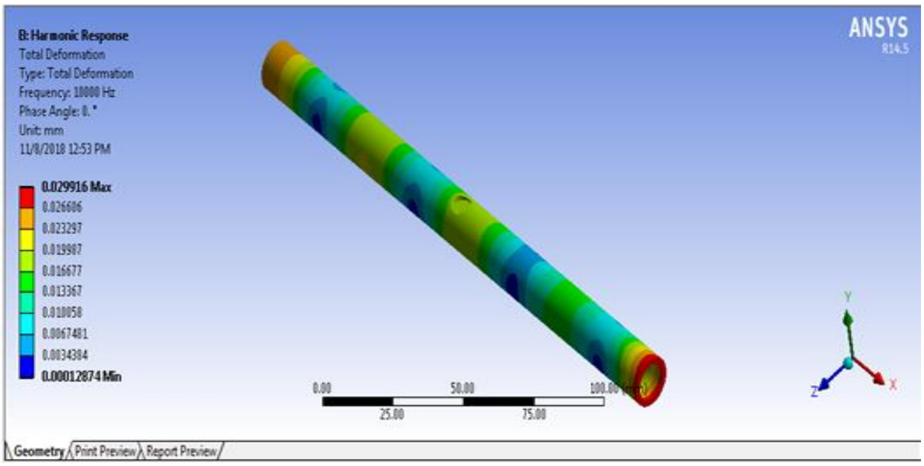


Figure 15. Deformation in a thin-walled pipe under IFL

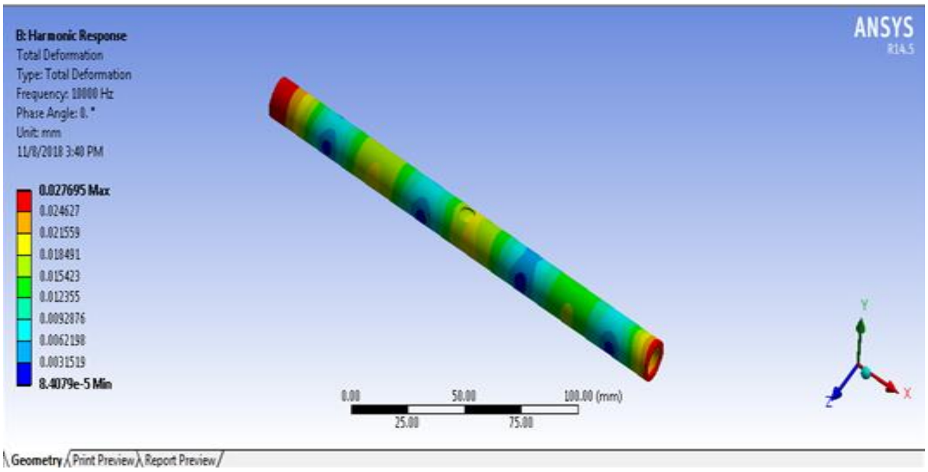


Figure 16. Deformation in a thin-walled pipe under OFL

Table 11. Initial and optimized fixture layout configuration

Variable	Initial Configuration (mm)	Optimized Configuration (mm)

	X	Y	Z	X	Y	Z
L_1	5.1	-5.1	75	5.1	-5.1	41.67
L_2	-5.1	-5.1	75	-5.1	-5.1	41.67
L_3	5.1	-5.1	-75	5.1	-5.1	-80.17
L_4	-5.1	-5.1	-75	-5.1	-5.1	-80.17
L_5	0	0	-100	0	0	-100
C_1	0	7.25	75	0	7.25	41.67
C_2	0	7.25	-75	0	7.25	-80.17

3.2. Optimization of Clamping Forces

After optimizing the initial fixture layout, the force-moment method was applied to the free body diagram (FBD) of the workpiece, as illustrated in Fig. 9. Clamping forces were computed at two load steps by solving the force-displacement matrix using MATLAB. The optimized clamping forces were lower than the initially assumed values, with the maximum force applied at each clamp to ensure firm holding of the pipe during the machining process. The optimized clamping forces calculated for each load step are presented in Table 12.

Table 12. Clamping forces at two load steps

Load-Step	Clamping force (C_1)	Clamping force (C_2)
1	-0.747	-51.14
2	-49.28	-758.75

So, the optimized clamping forces for min deformation and stability of fixture taken are: $C_1 = -49.28$, $C_2 = -758.75$. These forces were applied using vertical JS toggle clamps (Table 13).

Table 13. Toggle clamps model for optimum clamping forces

Toggle clamp model	Max capacity (kg)
$V105$	55
$V130$	225

3.3. Deformation after Optimization of Clamping Forces

The minimum workpiece deformation is again calculated by performing the harmonic analysis on the ANSYS workbench (Figure 17). After applying the optimized clamping forces at the optimized fixture layout, comparison shows that workpiece deformation is reduced significantly from $0.027698mm$ to $0.020854mm$. Table 14 shows that the workpiece deformation value reduces significantly at the optimized fixture layout and optimized clamping forces as compared to the initial fixture layout.

Figure 18 shows the optimized fixture layout configuration using ANSYS Workbench. The optimized layout was then implemented in the SANPAK industry for drilling operations in Aluminum pipes of diameter $14.5mm$. This optimized fixture layout configuration increased dimensional accuracy and reduced rejection of parts from 5% to2%.

The optimized fixture layout helps reduce part rejection during the brazing operation, particularly in the installation of the charging valve (CV) and rod fitting/assembly, by minimizing deformation. Misalignment of the charging valve often leads to issues during assembly and gas charging. Additionally, inaccurate or oversized holes can cause blockage in the refrigeration passage due to filler rod intrusion during the brazing process. The optimization significantly lowers the average rejection rate. The case study detailing the fixture layout and corresponding data is presented in Table 15.

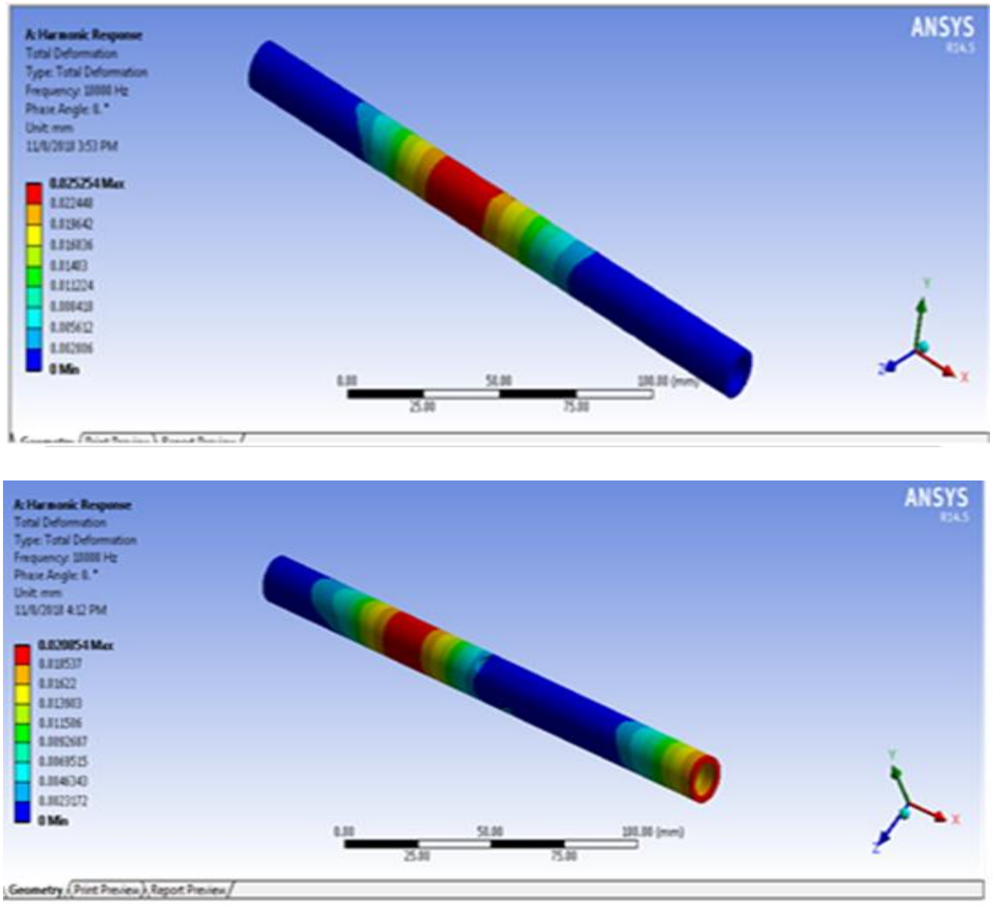


Figure 17. Max deformation before and after optimization of clamping forces.

Table 14. Workpiece deformation under different scenarios

Scenario	**Deformation (mm)**
Load step 1	0.056
Load step 2	0.0299
Initial fixture layout	0.0299
Optimized fixture layout	0.0277
Optimized clamping forces	0.0208

Table 15. Comparison of rejection rates before and after optimization.

	Month	**Total No. of Parts by lot no.**	**Rejection of Charging Valves due to Dimensional Inaccuracy**	**Blockage in the pipe due to a Rod inserted during brazing**	**Total No. of Rejections**	**Rejection %**	**Avg % Rejection**
Before fixture Layout Optimization	Sept. 2018	170	2	7	9	5.29%	5.17%
		150	3	5	8	5.33%	
		200	2	8	10	5.00%	
		296	5	10	15	5.07%	
	Oct. 2018	160	3	6	9	5.63%	5.13%
		175	2	7	9	5.14%	
		220	2	9	11	5.00%	
		294	5	9	14	4.76%	
		350	6	12	18	5.14%	

	Month	Total No. of Parts by lot no.	Rejection of Charging Valves due to Dimensional Inaccuracy	Blockage in the pipe due to a Rod inserted during brazing	Total No. of Rejections	Rejection %	Avg % Rejection
After Fixture Layout Optimization	March 2019	100	1	2	3	3.00%	2.24%
		160	0	3	3	1.88%	
		175	1	3	4	2.29%	
		220	1	3	4	1.82%	
	April 2019	144	1	3	4	2.78%	2.08%
		210	0	3	3	1.43%	
		292	2	4	6	2.05%	
		340	2	5	7	2.06%	

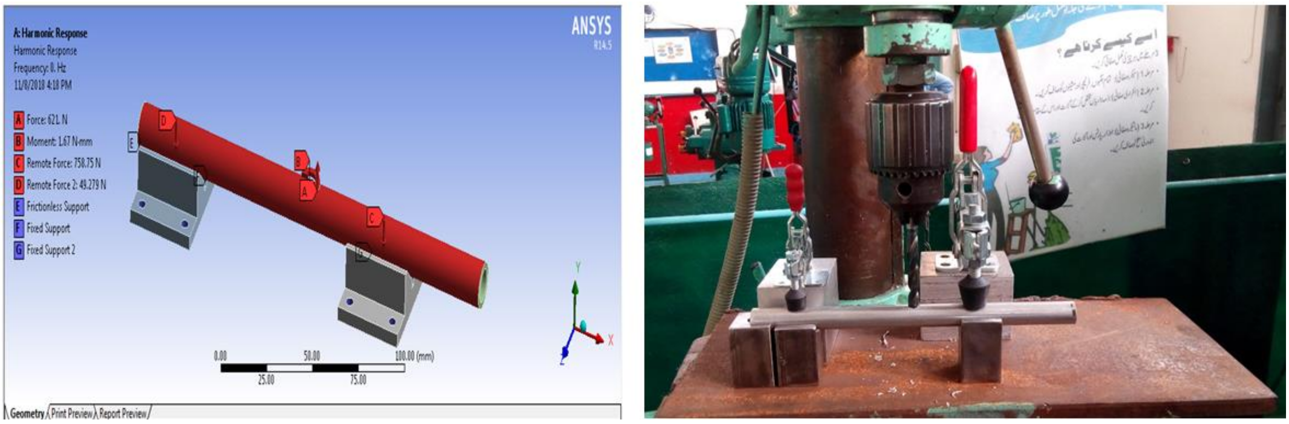


Figure 18. Final optimized fixture applied in the industry

3.4. Statistical Analysis

A **chi-square test of independence** to assess whether the observed reduction in rejection rate after optimization is statistically significant. The contingency table included the number of accepted and rejected cases before and after optimization. Table 16 indicates a highly significant association between the optimization and the decrease in rejection rate, providing strong statistical support for the effectiveness of the optimization strategy.

Table 16. Chi-Square Test of Independence for Rejection Rates

Statistical Measure	Value
Chi-Square Statistic (χ^2)	20.05
Degrees of Freedom (DoF)	1
P-value	< 0.00001
Significance Level	0.05

3.5. Performance Comparison after Optimization

Although both setups used the same physical fixture, significant improvements were achieved through optimization of clamping positions based on force-moment balancing. Previously, operators relied on experience and visual judgment to place clamps and align the part. The setup time estimation was broken down into realistic steps based on shop-floor observations:

- Pipe placement: 0.3 min (same for both scenarios)
- Clamp tightening and adjustment: 0.7 min (traditional), 0.5 min (optimized)
- Visual check / micro-adjustment: 0.5 min (traditional), 0.1 min (optimized)
- Final orientation confirmation: 0.3 min (traditional), 0.1 min (optimized)

This approach was generally fast (~1.8 minutes setup time) but introduced variability that contributed to a 5% rejection rate. After optimization, clamping positions were fixed and standardized, reducing trial adjustments and improving accuracy. This change eliminated minor delays and improved repeatability, reducing the setup time to 1.0 minutes and rejections to 2% as presented in Table 17.

Table 17. Performance Comparison of Fixture Layouts

Metric	**Traditional Fixture**	**Optimized Fixture**	**Improvement**
Max Deformation (mm)	0.0299	0.0208	31% ↓
Fixture Setup Time (min)	1.8	1.0	44% ↓
Fixture Efficiency (%)	–	45%	Based on deformation, setup time, and rejection rate reduction

4. ASSUMPTIONS & LIMITATIONS

The simulation assumes steady-state conditions and room-temperature operations. The influence of thermal gradients, machine vibrations, and real-time cutting force variations were not included. Boundary conditions were idealized based on the 3-2-1 locating principle, and frictional effects between fixture components and the workpiece were not explicitly modeled. The force-moment matrix assumes rigid-body behavior and static equilibrium at each discretized load step.

5. CONCLUSION AND FUTURE WORK

This study presents a robust methodology for the design and optimization of modular fixtures for cylindrical components using the Finite Element Method (FEM) in ANSYS. The integrated approach concatenates CAD modeling, FEM simulation, and clamping force optimization through a MATLAB-based force-moment matrix approach that minimizes workpiece deformation and improves fixture stability. The methodology was validated through an industrial case study involving HVAC aluminum pipes. Designs for round bar & pipe fixtures, as well as the clamping forces required to hold the workpiece, followed the same pattern. The optimized arrangement of the fixtures revealed that one V-Block locator needed to be placed close to the stopper and the other near the cutting tool. Application of the revised fixture architecture reduced the average part rejection rates from 5% to 2% and decreased setup time by 44%. These results demonstrate the practical advantages of the proposed fixture design approach in enhancing dimensional accuracy and operational efficiency. It is also possible to expand the work to include some more locators and clamps for more complicated work pieces.

For future work, this methodology can be extended to the design and optimization of fixtures for prismatic parts, which present a different set of geometric and force-distribution challenges. Adapting the current optimization framework to handle such complexities would expand the applicability of the approach.

“Nomenclatures		**Abbreviations**	
CV	Charging Value	FEA / FEM	Finite Element Analysis / Method
F_x, F_y, F_z	Force in x, y, z direction	ANN	Artificial Neural Network
M_p	Torque	CAD	Computer-Aided Design
Al	Aluminum	HVAC	Heating, Ventilation, and Air Conditioner
ρ	Density	FBD	Free Body Diagram
v	Poisson's ratio	IFL	Initial fixture Layout
E	Young's Modulus	OFL	Optimized Fixture Layout
		DOF	Degree of Freedom

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