RESEARCH AND APPLICATIONS ON ORIENTATION AND FIXING OF THIN-WALLED PARTS IN INDUSTRIAL CNC MACHINING SYSTEMS

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ABSTRACT: Precise machining of thin-walled parts such as aircraft components often made of aluminium or composites is critical for achieving the necessary dimensional accuracy and surface quality. However, the inherent vulnerability of thin-walled structures to deformation or damage during machining necessitates the development of orientation and fixing mechanisms to ensure accurate and stable positioning of the components. The paper discusses key elements of fixture design, analyses fixture positioning errors and their implications for manufacturing quality, studies the dynamic characteristics of thin-walled parts, and proposes an orientation and fixing device, with simulated operations for the manufacturing of a thin-walled aero engine component within a CNC machining system. The findings of this study emphasize the importance of fixture design in achieving precise and high-quality machining of thin-walled parts.

KEYWORDS: Thin-walled part, orientation, fixing, fixture design, CNC machining, simulation

1. Introduction

Fixtures are important devices in manufacturing as they hold the workpiece, position it correctly with respect to the machine tool, and support it during machining, directly impacting product quality, productivity, and cost. However, fixturing thin-walled parts is a challenging task, as these parts are susceptible to deformation or damage. Therefore, proper fixture design is necessary to hold the parts securely in place during machining or assembly operations without compromising their integrity. This is done through an extensive technical-economic analysis of interacting factors.

2. General considerations

2.1. Key elements of fixture design

Typically, fixture design involves the identification of locators, support points, and clamps, and the selection of the corresponding fixture elements for their respective functions. There are four main stages within a fixture design process: setup planning, fixture planning, fixture unit design and verification, as Fig. 1 illustrates [1].

A setup represents the combination of processes that can be performed on a workpiece without having to alter the position or orientation of the workpiece manually. During setup planning, workpiece and machining information are analysed to determine the number of setups required to perform all necessary machining operations and the appropriate locating datums for each setup [2].

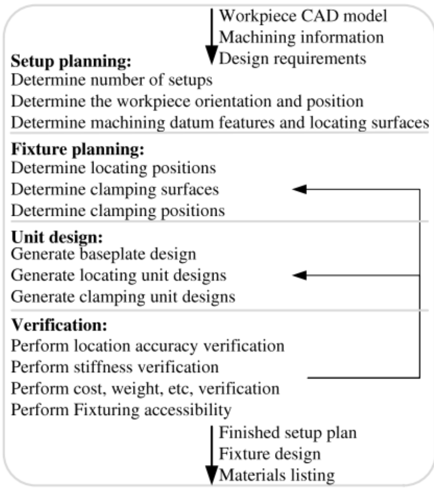


Fig. 1. The basic elements of the fixture design process [1]

During fixture planning, the surfaces, upon which the locators and clamps must act, as well as the actual positions of the locating and clamping points on the workpiece, are identified [1]. The number and position of locating points must be such that a workpiece's six degrees of freedom (Fig. 2) are adequately constrained during machining [2].

In the third stage of fixture design, suitable units, i.e., the locating and clamping units, together with the base plate, are generated. During the verification stage, the design is tested to ensure that all manufacturing requirements of the workpiece can be satisfied. The design also has to be verified to ensure that it meets other design considerations that may include fixture cost, fixture weight, assembly time, and loading/ unloading time of both the workpiece and fixture units [1].

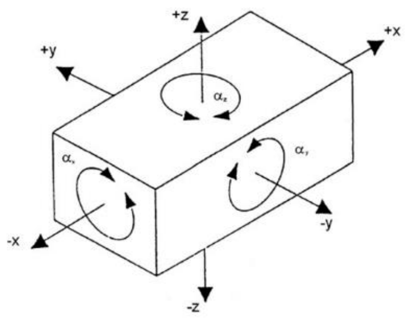


Fig. 2. The six degrees of freedom [2]

Typical example of a fixture is presented in Fig. 3. Clamps hold the workpiece against the locators during machining thus securing the workpiece's location.

The locating units themselves consist of the locator supporting unit and the locator that contacts the workpiece. The clamping units consist of a clamp supporting unit and a clamp that contacts the workpiece and exerts a clamping force to restrain it [2].

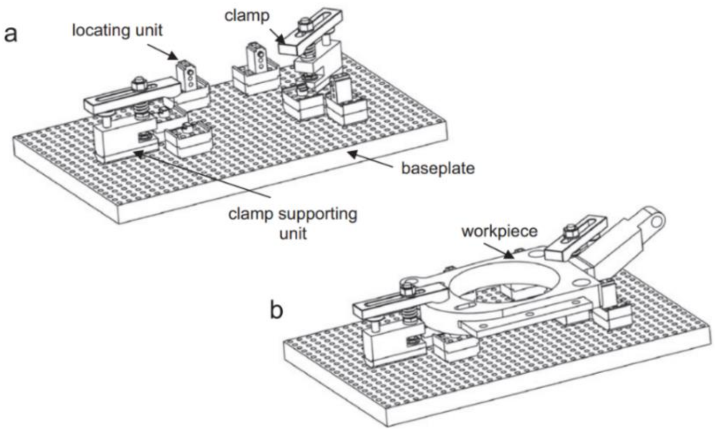


Fig. 3. A typical fixture (a) without and (b) with a workpiece [2]

2.2. Comprehensive analysis of fixture positioning errors and their implications for manufacturing quality

Fixture positioning errors refer to deviations in the placement or orientation of a fixture relative to its intended target or workpiece during machining or manufacturing processes.

The position errors of a thick block and a thin-walled workpiece in a fixture are presented in Fig. 4. In the locating stage, the locating error of the block and that of the thin-walled workpiece are the same δ_1. The difference is that the clamping deformation (δ_2) can be observed on the thin-walled workpiece in the clamping stage [3].

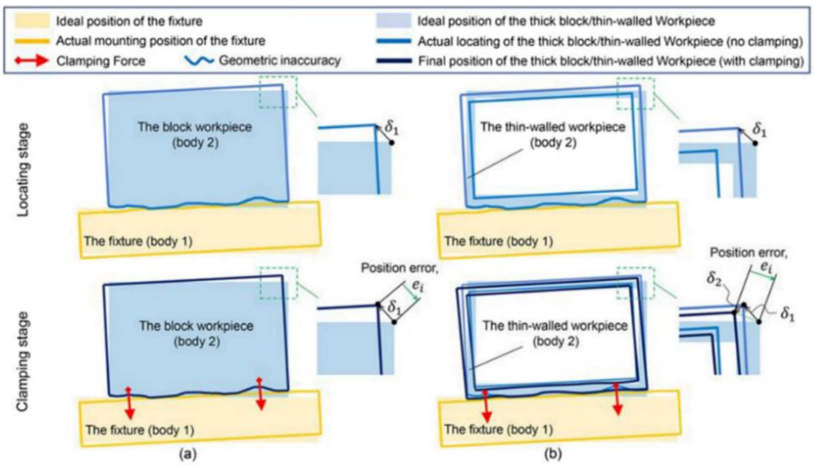


Fig. 4. Schematics of workpiece position error in the fixture emphasizing the key difference in deformation due to the clamping force: (a) thick block and (b) thin-walled workpiece [3]

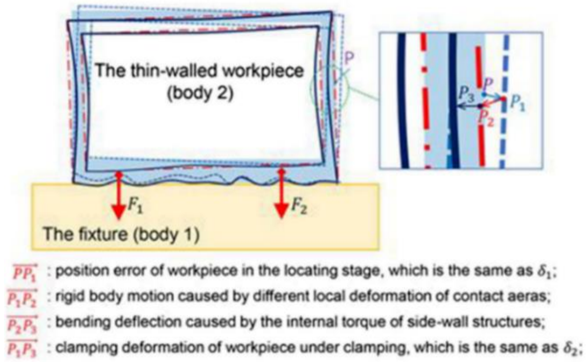


Fig. 5. The workpiece's deformation [3]

Further detailed analysis of the clamping deformation of the thin-walled workpiece is presented in Fig. 5. The position error of any point (P) of the thin-walled workpiece after the clamping stage can be given by [3]:

$$\vec{e_w}(P) = -\left[\vec{\delta_1} + \vec{\delta_2}\right] = -\left[\overrightarrow{PP_1} + \overrightarrow{P_1P_2} + \overrightarrow{P_2P_3}\right] \qquad (1)$$

Basically, tolerance represents the upper limit of permissible actual deviation from the nominal characteristic associated with a certain, given characteristic [5]. Inaccuracies in a fixture's location scheme result in a deviation of the workpiece from its nominal specified geometry as shown in Fig. 6. For any workpiece, this deviation must be within the limits allowed by the geometric tolerances specified.

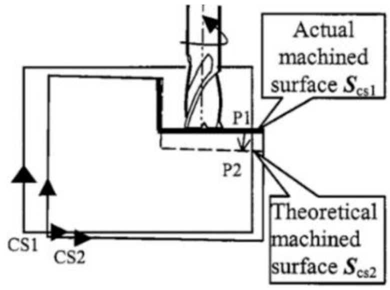


Fig. 6. Machined surface error [4]

2.3. Dynamic characteristics of thin-walled parts and analysis for compensating fixturing and machining errors

Thin-walled parts especially used in aerospace are difficult to machine due to their weak rigidity, complex shape, and structure. This makes the contact interface between tools and workpieces interact strongly. As material is removed during the machining process, the geometric structure of the workpiece changes continuously, leading to time-varying dynamic characteristics of the machining system. This makes it challenging to control the clamping deformation and maintain machining stability [6].

Quantitatively, rigidity, K, is the ratio between ΔF action force variation and ΔU generated deformation variation, i.e.,

$$K = \Delta F / \Delta U \qquad (2)$$

where the action force F can be type of: weight, inertia force, fixing/ clamping force, machining/ processing force or a combination/ resultant thereof. The deformation U can be: elastic deformation, plastic deformation, displacement caused by clearences from joints or a resultant thereof [7].

Typical fixture configurations modeled to simulate transient thermo-mechanical analysis and to visualize workpiece non-linear behaviour during the material removal process due to its changing rigidity, in-elastic material properties and flexible fixture contacts are presented in Fig. 7.

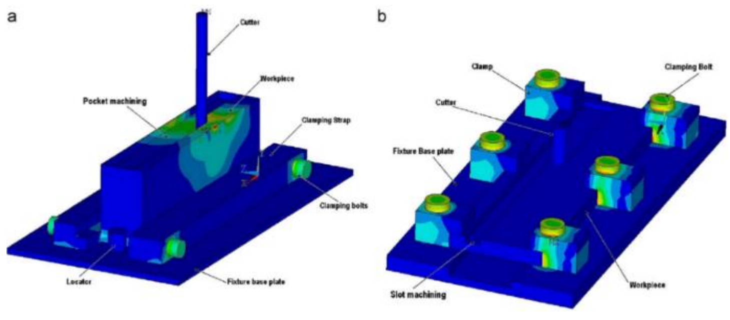


Fig. 7. Developed fixture configurations. (a) Fixturing using strap clamps (b) Fixturing using wedge clamps [8]

Analysis is performed by applying appropriate boundary conditions such as clamping loads calculated using Eq. (3), fixturing constraints, etc. on the fixture-workpiece FEM model [8].

$$F_{clamp} = \frac{T}{0.2 * D_b} \qquad (3)$$

where F_{clamp} is the clamping force (N), T - the applied torque (Nmm) and D_b the bolt nominal diameter (mm).

During the manufacturing process, clamping forces of active fixtures can be adjusted according to the FEA result to compensate for machining errors, or adjust suitable clamp forces to generate adequate contact forces and pressure distribution at the contact region to keep the workpiece in position during machining [1].

In a particular case, the existing clamping and machining strategy cause large local contact deformations as well as structural deformations of the part. As a result, the workpiece wall thickness and geometry are out of tolerance with poor surface finish. A static analysis is carried out in ANSYS, by modelling fixture elements and workpiece assembly using frictional contacts to investigate the workpiece deformations for various wall thicknesses and clamping pressures [9].

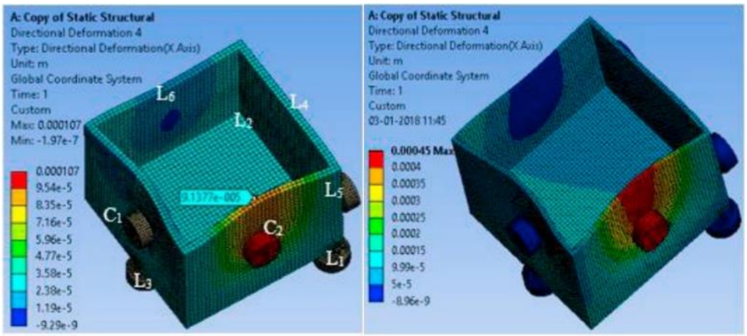


Fig. 8. Static FEA showing deformations of 4.5 mm and 2.5 mm thick workpiece subjected to localized pressure at contact in a 3-2-1 workpiece-fixture system [9]

3. Case study

The case study refers to manufacturing of a thin-walled aero engine part (Fig. 9) within a CNC machining system, with focus on fixture and machining operations design, including simulations.

One technological variant has been developed [7], with respect to the main technical requirements, namely maximum rigidity of the part - fixture subsystem, for minimizing deformation, and ensuring accessibility.

3.1. Fixture design

The proposed fixture design for orientation and fixing of the considered thin-walled aero engine part has been carefully developed based on a comprehensive analysis of the component's geometry, material properties, and machining process requirements.

The fixture design proposal effectively addresses the previously stated challenges posed by the complex geometries and lightweight material properties of the component.

The fixture assembly is shown in the Fig. 10 without a workpiece, allowing for a clear view of its components and construction.

Fig. 9. Part to be machined

Fixture consists of base plate, screws, bolts, nuts and washers [10]. The base plate features a platform shaped to match the external profile of the part, with a slight offset towards the center to prevent tool crashes and minimize friction during machining of features on the bottom side. The device, through its base plate, is securely fixed to the CNC machine table using screws that pass-through counter-bored holes beneath the surface and meet T-slot nuts, providing an unobstructed machining area for the tool.

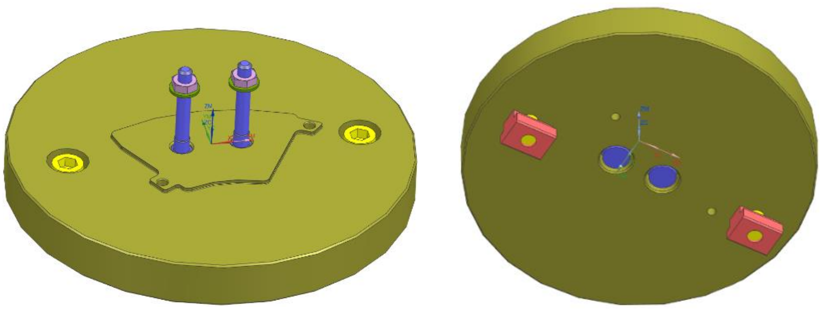
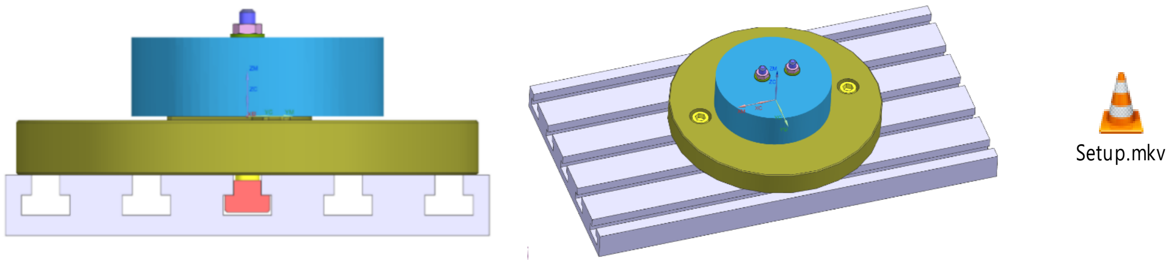


Fig. 10. Fixture without workpiece

Raw material initially went through turning, drilling and boring machinings to be prepared for CNC operations.

The proposed fixture is implemented in the technological machining system for the first two CNC machining operations.

Thus, the workpiece is oriented through bolts and fixed to the base plate using the elements screw-nut, as shown in Fig. 11.



a. b. c.

Fig. 11. Fixture with workpiece (a, b); Set-up (c)

3.2. Technological operations structure and simulations

As the workpiece is subjected to the precision of machining, it undergoes a transformation from its initial cylindrical shape, with the gradual emergence of finely crafted thin walls, until it ultimately achieves the exacting form required.

To achieve this, a machining strategy is employed whereby the workpiece held by bolts in the central area, and the machining process is performed around the center as shown in Fig. 12. A thin wall is retained horizontally in the middle to keep this connection. lt will be removed in the final operation. This approach allows for precise machining of the part while maintaining structural integrity, as the thin wall acts as a support structure.

Operation 1 involves external and internal milling, centering, and drilling processes (Fig. 13, 14). The machined surfaces are indicated with thicker lines.

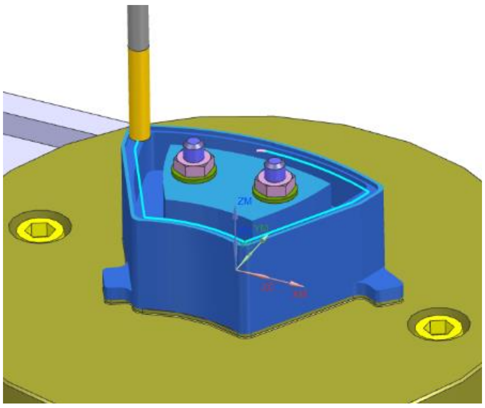


Fig. 12. Machining simulation

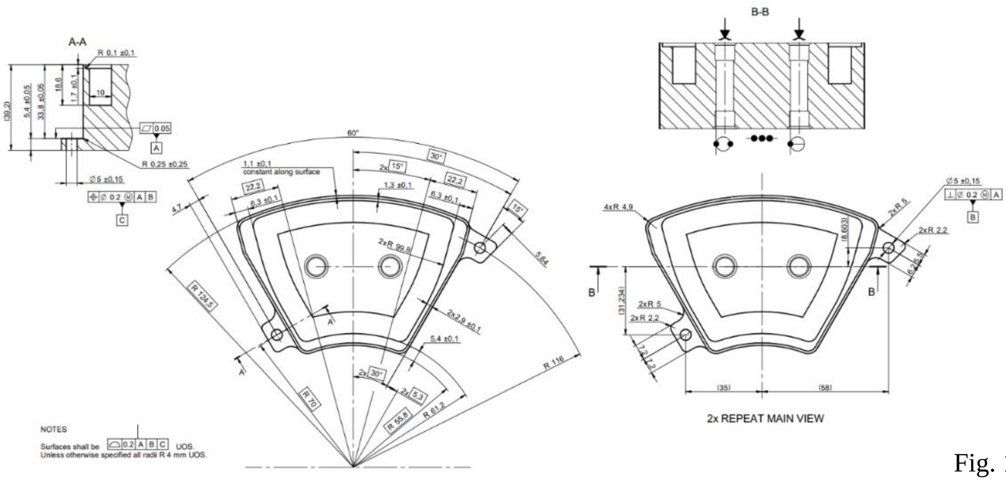
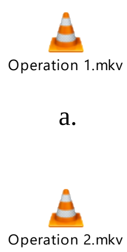


Fig. 13. Technological operation sketch 1



a.

b.

Fig. 14. Simulations:
a- Operation 1; b- Operation 2

In Operation 2, the part is placed upside down and internal pocket is machined, at this point the thin wall appears in the middle (shown in Fig. 14, 15) which will have the connection element role during all operations as previously stated.

After all machining phases including further ones simulated in Siemens NX, and part verified, the program is translated into machine-specific instructions meaningly the G-code is generated by post processing. Once the CAM programming is complete and the machine is set up, the manufacturing process can begin. The CNC machine executes the toolpaths generated by the CAM software to create the physical part.

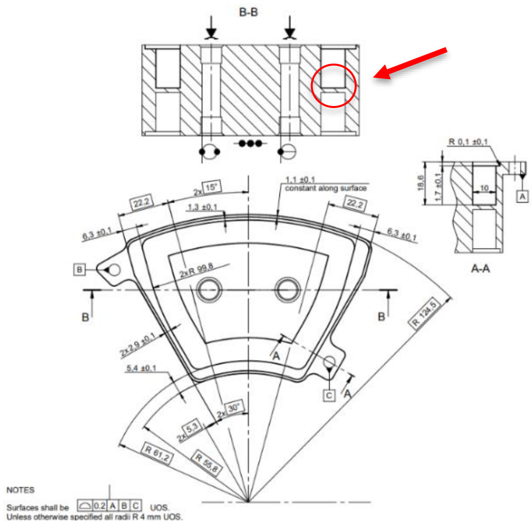


Fig. 15. Technological operation sketch 2

4. Conclusions

This study focuses on the advancements in precision manufacturing through research on orientation and fixing of thin-walled parts. Through analysing fixturing errors and investigating the dynamic characteristics of thin-walled parts, the need for specialized fixture to ensure accurate and stable positioning during machining has been demonstrated.

The proposed fixture design for the manufacturing of a thin-walled aero engine component within a CNC machining system serves as an effective variant of orientation and fixing device. The study's findings contribute to the body of knowledge on fixture design and its impact on manufacturing quality in the aerospace industry.

Furthermore, future research may consider optimizing fixture design with respect to the manufacturing technological process variants to enhance manufacturing efficiency, reduce costs, minimize waste, and improve product quality.

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