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REVIEW ARTICLE

Fixturing technology and system for thin-walled parts machining: a review

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ABSTRACT During the overall processing of thin-walled parts (TWPs), the guaranteed capability of the machining process and quality is determined by fixtures. Therefore, reliable fixtures suitable for the structure and machining process of TWP are essential. In this review, the key role of fixtures in the manufacturing system is initially discussed. The main problems in machining and workholding due to the characteristics of TWP are then analyzed in detail. Afterward, the definition of TWP fixtures is reinterpreted from narrow and broad perspectives. Fixture functions corresponding to the issues of machining and workholding are then clearly stated. Fixture categories are classified systematically according to previous research achievements, and the operation mode, functional characteristics, and structure of each fixture are comprehensively described. The function and execution mode of TWP fixtures are then systematically summarized and analyzed, and the functions of various TWP fixtures are evaluated. Some directions for future research on TWP fixtures technology are also proposed. The main purpose of this review is to provide some reference and guidance for scholars to examine TWP fixtures.

KEYWORDS thin-walled part (TWP), fixture, machining, fixture categories, fixture function

1 Introduction

Thin-walled parts (TWPs) are widely used in sophisticated equipment in aerospace, automobile, shipping, nuclear industry, and other fields [1]. However, the characteristics of TWPs, such as their low stiffness, uneven stress distribution, and strong time-varying characteristics, inevitably lead to some machining-induced problems, including deformation, vibration, and low efficiency, during the overall processing, thereby reducing surface integrity [2] and geometric accuracy [3]. Ultimately, the service performance and life of TWP gradually decrease. Therefore, the precision machining of TWP has received much scholarly attention. At present, optimizing fixture modes is a popular approach for improving the machining process of TWP and final machining quality.

A complete manufacturing system comprises a machine tool, a workpiece, and a fixture, with each element playing a key role in the system and interact with one another. Machine tools are considered "troublemakers" in the machining process that lead to many issues depending on the characteristics of TWPs, thereby affecting the stability of the processing and the final quality of manufactured parts. Meanwhile, the fixture is considered a "troubleshooter" that restrains these machining problems. Workpieces can be perceived as an arena that hosts the battle between the "troubleshooter" and the "troublemaker." In sum, as a key element of the manufacturing system, the fixture has an important impact on the machining process [4] and directly determines the final quality of TWPs [5].

Some studies have highlighted the importance of the fixture in the manufacturing process. For instance, Brecher et al. [6] divided the machining into the manufacturing process and a machine tool by analyzing in depth the interaction phenomena in a machine tool. The manufacturing process comprises three elements, namely, a workpiece, a manufacturing technology, and a tool, whereas the machine tool also has three elements, namely, a machine structure, controls, and a clamping fixture. The interactions among these elements can be considered a complete and indivisible system that always exists in production machines and determines the analysis

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and optimization of the processing. According to Brecher et al. [6], as one of the six key elements, fixture technology plays an indispensable role in the interactive system. Hansel et al. [7] used manufacturing process analysis techniques to improve the geometric accuracy of the computerized numerical control (CNC) machine tool. First, they established a high-fidelity model corresponding to manufacturing error established by utilizing simulation techniques to clearly analyze the processing. Afterward, based on the analysis results, they optimized the processing and fixture design to improve the geometry accuracy of workpieces. The effect of fixture on the machining process was fully considered in their research.

In this review, the categories and functions of the TWP fixture are analyzed and summarized systematically to provide some reference and guidance for future studies on advanced TWP fixture. This key review is organized as follows (Fig. 1). First, after briefly discussing the key role of fixture in the manufacturing system, this review analyzes the problems in the manufacturing process of TWP, which mainly include vibration, deformation, and damage. Second, the definition of TWP fixtures is reinterpreted from the narrow and broad perspectives. Third, the TWP fixtures are systematically categorized, and the operation mode and structural characteristics of each fixture are described. Fourth, the fixture functions related to the manufacturing issues are presented and divided into basic and additional functions. Furthermore, the implementation model of fixture functions is analyzed and discussed item by item. Fifth, the conclusions of this paper are presented along with directions for future research.

2 Interaction of fixture and machining process

2.1 Problems in machining process

During the overall processing, the TWP faces various manufacturing environments, such as milling, grinding, welding, and drilling [8]. As a difficult-to-machine material, TWP typically has low stiffness, strong time-varying characteristics, uneven stress distribution, and complex and diverse geometry, which mainly lead to machining-induced problems (Fig. 2). The main problems in the manufacturing process of TWP are summarized below.

Vibration: During the material removal process, vibration associated with low rigidity occurs due to the dynamic compliance of TWP and the excitation from the machining operation [9]. This vibration poses a serious challenge to a reliable fixation and stable machining [10]. Machining-induced vibration is also the main source of manufacturing errors [11] as reflected in poor surface quality [12]. Vibration also causes tool wear [13] and shortens tool life [14].

Deformation: According to inducible factors, TWP deformation can be divided into mechanical- and thermal-induced deformations [15]. Under most conditions, TWP deformation is a result of mechanical-thermal coupling. Low structural stiffness and uneven stress distribution are major causes of TWP deformation [16], which negatively affects the machining process and the final machining quality unless the aforementioned problems are suppressed. The problems caused by deformation during machining mainly include position error and cutter back-off,

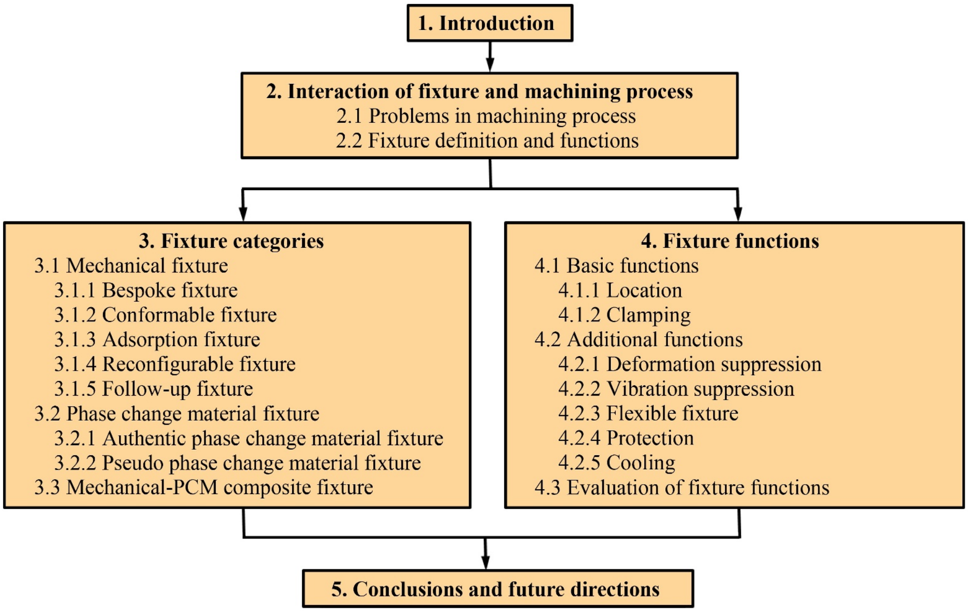
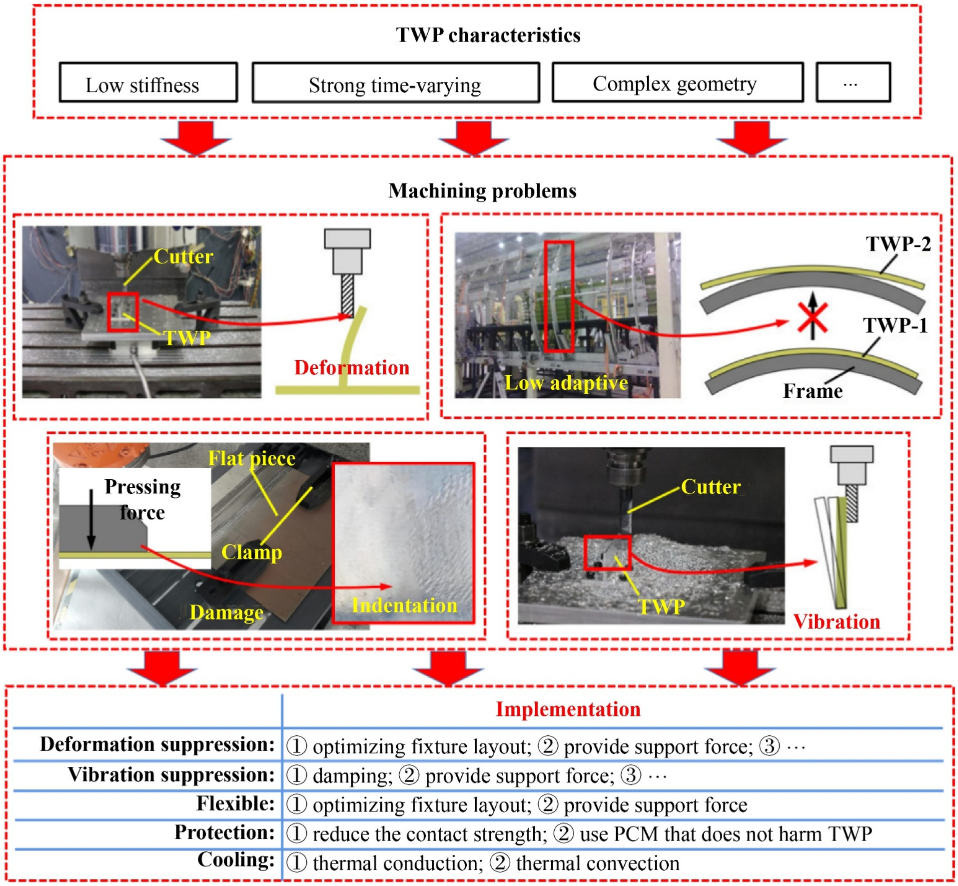


Fig. 1 Overall structure of the present work.



	Implementation
Deformation suppression:	① optimizing fixture layout; ② provide support force; ③ ···
Vibration suppression:	① damping; ② provide support force; ③ ···
Flexible:	① optimizing fixture layout; ② provide support force
Protection:	① reduce the contact strength; ② use PCM that does not harm TWP
Cooling:	① thermal conduction; ② thermal convection

Fig. 2 Machining-induced problems of thin-walled part (TWP). PCM: phase change material.

whereas the negative effects of deformation on the final machining quality include poor surface quality [17], low geometry accuracy [18], and residual stresses [19].

Damage: Given the high contact strength between the fixture and TWP, different forms of damage, including indentations, scratches, and clamping deformations, often occur on the TWP surface [20]. Fixture-induced damage negatively influences the workholding effect and quality of TWP.

Low adaptability: The low adaptability of the TWP fixture is mainly manifested in the aspects of force and layout. First, the force provided by the fixture cannot easily respond to the changes in the machining load and hence provides sufficient support to offset the machining load, which eventually leads to poor machining accuracy [21–23]. Moreover, the fixture cannot easily adapt to the machining process and geometric structure of TWP by adjusting own layout, which means that the fixture itself has few adjustable elements or the fixture elements have a limited adjustment range.

2.2 Fixture definition and functions

Workers traditionally use fixtures to keep workpieces in a specific position during machining. At this stage, the TWP fixture definition (i.e., narrow fixture) is used to fix the machined object in order for this object to occupy the correct position and accept the machining. In modern industries, given the improved performance of advanced equipment for TWP, the manufacturing precision of TWP has received much scholarly attention. Specifically, scholars have started exploring the machining-induced problems of TWP (e.g., vibration and deformation) and the influence of the fixture on TWP quality (e.g., adaption and clamping stress) and even devoted some effort to improving the machining conditions of TWP by optimizing the fixture method in order to suppress machining-induced problems and subsequently improve the final machining quality. At this time, the TWP fixture definition (i.e., broad fixture) not only holds the object at a specific position during processing but also efficiently suppresses the machining problems.

Following the above discussion, fixture functions can be divided into basic and additional functions (Fig. 3). Basic functions refer to the location and clamping of TWP, whereas additional functions refer to suppressing the machining-induced problems of TWP. The narrow fixture only has basic functions, whereas the broad fixture has both basic and broad functions. These basic and broad functions can be defined as:

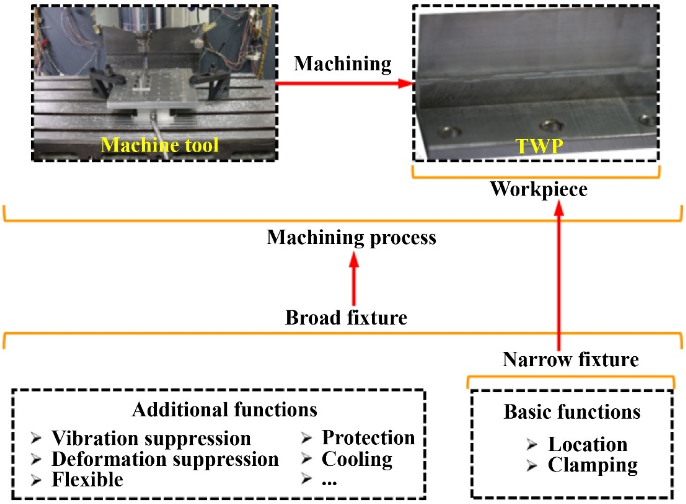


Fig. 3 Narrow and broad fixtures for thin-walled part (TWP).

Basic functions:

Location: Limit the degrees of freedom (DOFs) of TWP to guarantee location accuracy in the 3D coordinate system.

Clamping: Fix the workpieces in a specified position against any manufacturing forces.

Additional functions:

Vibration suppression: Absorb or transfer machining-induced vibration by damping elements on the fixture or provide a clamping and supporting force suitable for processing load to reduce vibration.

Deformation suppression: Adjust the fixture layout and the supporting state to adapt to the surface geometry of TWP and the machining process in order to reduce machining deformation.

Flexible: Optimize the layout, structure, and operation mode of the fixture to adapt to the structure and processing of TWP in order for the fixture to meet the fixation requirements of all types of TWPs.

Protection: During the clamping process, the fixture neither damages the TWP nor provides safety protection at the contact between the fixture and TWP surface to avoid clamping-induced damage, such as clamping stress and scratches.

Cooling: Cool the TWP via thermal conduction and thermal convection to reduce thermal stress.

3 Fixture categories

TWP fixtures need to adapt to the structure and machining process of the TWP to meet the precision machining requirements, ensure the stability of processing, and achieve great workpiece quality. Therefore, in recent years, TWP fixtures have been continuously innovated by scholars in terms of their structure, materials, and operation methods. Many types of fixtures are currently applied to TWP processing. Following previous research, TWP fixtures can be categorized into mechanical and phase change material (PCM) fixtures. Based on their structure and holding method, mechanical fixtures can be further classified into bespoke fixtures (BFs), conformable fixtures (CFs), adsorption fixtures (AFs), reconfigurable fixtures (RFs), and follow-up fixtures (FUFs). Among these fixtures, CF can be further divided into single- and double-side CFs, AF into sucker-, hole-, and slot-based AFs, RF into affordable reconfigurable tooling (ART) and modular fixture (MF), and FUF into mirror support (MS), multi-robot system (MRS), and jet support (JS). Meanwhile, PCM includes authentic phase change material (APCM) and pseudo phase change material (PPCM) fixtures, of which APCM can be further divided into ice-based fixtures (IBFs), paraffin fixtures (PFs), and low-melting alloy (LMA) fixtures, whereas PPCM can be divided into magnetorheological fluid (MRF) fixtures, electrorheological fluid (ERF) fixtures, and iron-powder-based fixtures (IPBFs). Moreover, the mechanical-PCM composite fixture mainly includes the mechanical-MRF and mechanical-LMA composite fixtures. These fixture categories are summarized in Table 1 [20,22,24–67].

3.1 Mechanical fixture

3.1.1 Bespoke fixture

BF is a traditional fixture that is designed and manufactured with reference to workpiece geometry and the manufacturing process (Fig. 4). The precision of BF depends on the level of manufacturing technology. With few to no adjustable elements, BF offers low flexibility. Meanwhile, the high manufacturing costs resulting from long production cycle and low adaptability limit the continuous usage of BF in the manufacturing industry.

Table 1 Fixture categories

Category I	Category II	Category III	Ref.
Mechanical fixture	BF	–	Yan et al. [24], Qi et al. [25]
	CF	Single-side CF	Aoyama and Kakinuma [26], Walczyk and Longtin [27], Li et al. [28]
		Double-sides CF	Craig et al. [29], Al-Habaibeh et al. [30]
	Vacuum adsorption fixture (VAF)	Sucker-based VAF	He et al. [31], Qi et al. [32], Liu et al. [33]
		Hole-based VAF	Yang et al. [34]
		Slot-based VAF	Rubio-Mateos et al. [35,36]
	RF	ART	Kihlman and Engstrom [37,38], Zhang et al. [39], Jonsson et al. [40]
		MF	Cioată et al. [41], Wang et al. [42], Croppi et al. [43], Nee et al. [44]
	FUF	MS	Bao et al. [45,46], Xiao et al. [47]
		MRS	Veeramani and Muthuswamy [48], de Leonardo et al. [49], Sagar et al. [50]
		JS	Liu et al. [51], Rajaratnam and Albers [52]
PCM	APCM	IBF	Wang et al. [53], Liu et al. [22], Mironova et al. [54–56]
		PF	Zha et al. [57], Ge et al. [58], Gao et al. [59]
		LMA	Wang et al. [20], Saito et al. [60], Lee et al. [61–63]
	PPCM	MRF fixture	Liu et al. [64], Ma et al. [65]
		IPBF	Liu and Ke [66,67]
Mechanical-PCM composite fixture	Mechanical-MRF composite fixture	–	Veeramani and Muthuswamy [48], de Leonardo et al. [49]
	Mechanical-LMA composite fixture	–	Aoyama and Kakinuma [26], Al-Habaibeh et al. [30]

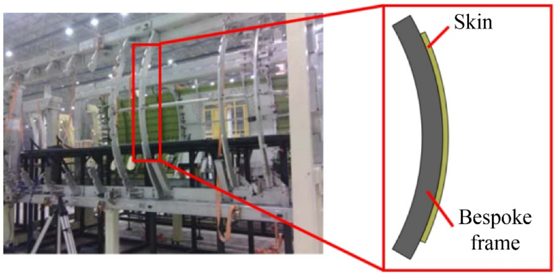


Fig. 4 Bespoke fixture for aircraft skin assembly and processing.

However, with the increasing level of industrial manufacturing, BF has demonstrated improvements in its accuracy despite still encountering fixture errors [24]. To reduce workpiece deformation errors, the fixture element layout for a given part is usually optimized at the design stage, while some researchers have provided an error compensation for finished BF to suppress workpiece deformation based on the error analysis model [25]. When designing BF for TWP with large surface profiles, a contact gap is inevitably formed between the TWP surface and BF due to the geometrical error of the fixture, which leads to unacceptable deformation and vibration that weaken the stability of the machining system. Unfortunately, this TWP–BF gap cannot be completely eliminated. However, given that the design and manufacture of BF are less difficult than those of other fixtures, BF can still be used in some manufacturing factories. Given that BF cannot easily adapt to the development requirements of modern high-precision machining, this fixture is expected to be replaced by flexible and automated fixtures in the future.

3.1.2 Conformable fixture

CF is a conformable and non-traditional flexible fixture with the potential to improve dimensional accuracy and surface integrity and to increase the number of components that are manufactured correctly for the first time. The principle of CF is that the positions of the support elements are mechanically and freely adjusted to conform to variational workpiece geometry [68]. Structurally, CF can be divided into double- (Fig. 5(a) [29]) and single-side CF (Fig. 5(b) [26]), which serve different purposes. On the one hand, double-side CF achieves clamping by conforming to the double surface of TWPs (Fig. 5(c)). On the other hand, single-side CF plays a supporting role in the manufacturing process (Fig. 5(d)).

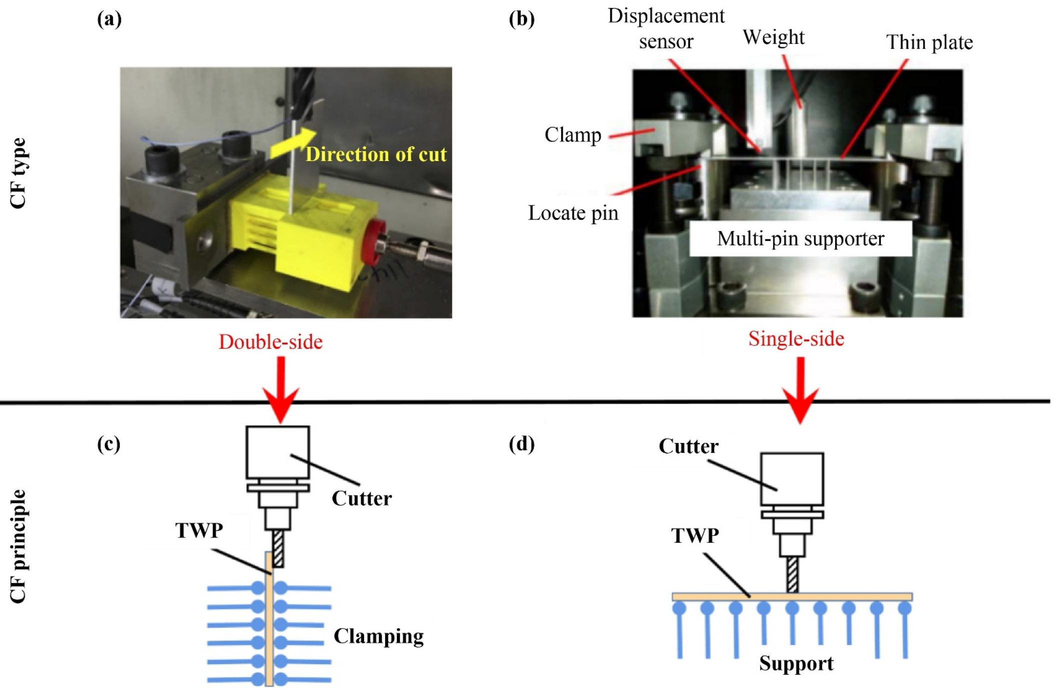


Fig. 5 (a) Double-side CF [29], (b) single-side CF [26], (c) clamping function of double-side CF, and (d) support function of single-side CF. CF: conformable fixture. Reproduced with permissions from Refs. [26,29] from Elsevier.

CF is highly self-adaptive, which helps shorten the development cycle and save costs [69]. Moreover, the support elements covering the surface profile of TWPs greatly enhance their structural rigidity during the manufacturing process, simultaneously weaken the impact of the processing on their geometric accuracy, and suppress machining-induced deformation. Some studies have shown that CF can also act as a vibration suppressor. Craig et al. [29] adopted double-side CF to clamp the TWP, carried out milling experiments, and found that this double-side support can greatly reduce vibration. Moreover, to improve the damping effect of CF on machining-induced vibration, a fixture mode combining APCM with array pins systems was proposed innovatively [26]. This method inserts support pins into APCM and uses the phase-change properties of APCM to control the motion of these pins. Meanwhile, the damping of APCM can suppress the vibration transmitted by the rod. In terms of automation, CF can be easily configured with actuators and sensors and achieve a precise adjustment of the movement of support pins via an integrated control system. This automatic mode of CF greatly improves the efficiency of adjusting CF and, most importantly, reduces the need for manual operation, thereby reducing the risk of personal errors.

Nevertheless, CF still has a large room for improvement. First, support pins can move only in the axial direction of the pin and cannot easily move in the direction perpendicular to the axis of the rod. This defect can only be addressed by increasing the density of support pins, which would entail higher costs and more complicated control processes. Second, the gap between the support pins and TWP surface generates an incomplete machining support, which eventually leads to surface deformation and machining instability.

According to the motion control mode of support pins, CF can be classified into PCM- (Fig. 6(a)), plate- (Fig. 6(b)), and motor-based CFs (Fig. 6(c)). Aoyama and Kakinuma [26] designed a PCM-based CF comprising support pins, a chamber of LMA, and a heater plate. The upper part of the support pin is in contact with the workpiece surface, whereas its lower part is immersed in a chamber filled with LMA. This LMA is sealed in a chamber by a separate plate and begins to melt as the chamber temperature is increased by the heater plate. As a result, all support pins move up due to the buoyancy force until they touch the surface of the TWP; the LMA in the chamber is then cooled, and all the pins are fixed rigidly due to the phase change of low melting alloy from liquid to solid [30]. The support pins can move freely along the axis of the pins within PCM, hence enabling them to conform to the geometric shape of TWP, while the damping property of PCM weakens the machining vibration of the supported workpiece. However, PCM is harmful to the environment and operators, and the phase change process consumes much heat. These issues limit the developments of PCM-based CF. Walczyk and Longtin [27] developed a plate-based CF to hold TWPs and controlled the upward and downward movements of the support pins by using a rigid plate. First, the plate extends the free-moving support pins to the highest position. Second, the plate slowly descends, and each pin

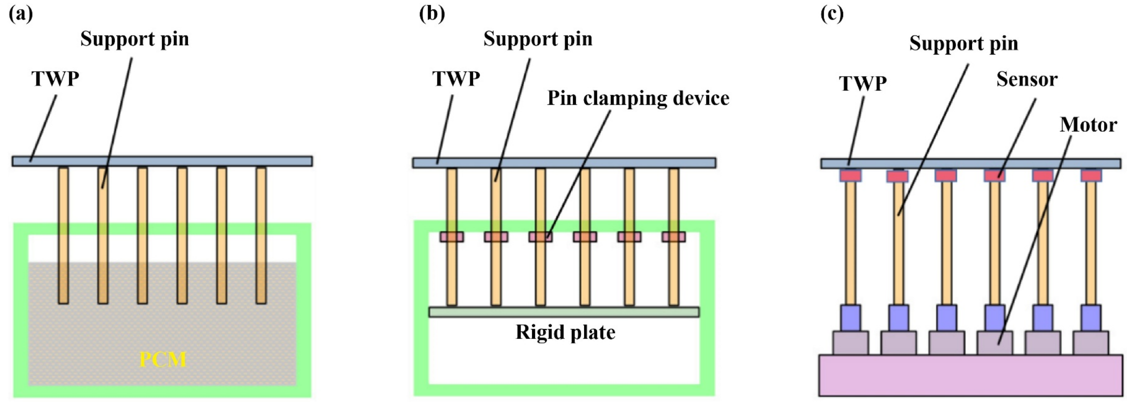


Fig. 6 Schematic diagram of the motion control mode of support pins: (a) PCM-based CF, (b) plate-based CF, and (c) motor-based CF.

can be held in specified position based on the TWP geometry. In this way, array pins can fully conform to the underside surface of the TWP. Other researchers have often used motor actuators to the motion control of the support rods/pins. Integrated with sensors and motor actuators, motor-based CFs are highly adaptive to the process and are more automated than either PCM- or plate-based CF. To reduce the distortion triggered by the non-uniform thermal gradients in the additive manufacturing process, Li et al. [28] designed a flexible multi-point support fixture (FMSF) made up of support pins, a force cell, a DC motor, and an encoder. This FMSF can adjust the restraint force of support pins on the substrate based on the force and displacement signals acquired by the force cell and encoder, respectively, to effectively suppress angular and bending distortions. CF is also highly adaptive to the surface geometry of the workpiece and has wide application prospects in the fixation of TWPs with complex surfaces.

3.1.3 Adsorption fixture

AF is a quick clamping technology. Among its types, vacuum adsorption fixture (VAF) is the most common and widely used for clamping curved TWPs and flat parts. VAF utilizes air pressure to clamp workpieces, and the air pressure acting on the surface of the TWP can be precisely controlled by changing the vacuum degree of suckers. Compared with other mechanical fixtures, VAF can quickly achieve workholding as long as the TWP can be sealed. Therefore, VAF can greatly avoid the cumbersome installation and disassembly processes of fixtures, hence increasing production efficiency. Furthermore, VAF neither damages the surface nor requires much time or labor to align TWP. This fixture is also environment friendly and does not consume energy, such as light, heat, and electromagnetism. Moreover, the latest VAF system is automated, can quickly replace workpieces of different specifications and shapes, and is highly compatible with CNC machine tools. However, as VAF is generally made of rubber and come sin direct contact with objects, this fixture is prone to fast and very serious wear, which would eventually deflate the suckers and weaken its stability. As a result, the maintenance of the VAF system is very expensive and only adds up to the manufacturing cost.

Functionally, the absorption unit is the basic functional element to achieve clamping. According to the structure of the absorption unit, VAF can be mainly classified into sucker- (Fig. 7(a)), hole- (Fig. 7(b)) [34], and slot-based VAFs (Fig. 7(c)) [35]. The sucker-based VAF can be further divided into multi-sucker and single-suck VAFs [31], whereas the hole-based VAF is mostly multi-hole VAF. In terms of their adaptability to the structural changes of TWP, multi-sucker VAF is the strongest among the three aforementioned VAFs, which can arbitrarily change the position and posture of the suckers, optimize the layout of the VAF unit [32], and reconfigure the VAF structure to adapt to the surface geometry and manufacturing process of TWP so as to achieve stable clamping and minimize the deformation induced by processing and holding. In terms of the rigidity of suckers, the multi-sucker VAF has strong and weak rigid suckers. On the one hand, strong rigid suckers not only clamp TWP but also use their own rigidity to support the workpiece surface and avoid undesirable deformation induced by gravity and machining load. On the other hand, weak rigid suckers are not capable of supporting the TWP surface. Therefore, some researchers have installed support heads inside weak rigid suckers to address this limitation [33]. Auxiliary devices are also often used to help the suckers support the workpiece surface. Multi-sucker VAF is often used to hold medium to large TWPs but is not suitable for large-radian TWPs, such as spherical shells, mainly because suckers will detach from the TWP surface. Therefore, the single-suck VAF is often used to hold large-radian TWPs. However, this type of VAF has poor flexibility, and sometimes the size and structure of the sucker need to be specially designed according to the workpiece geometry to achieve

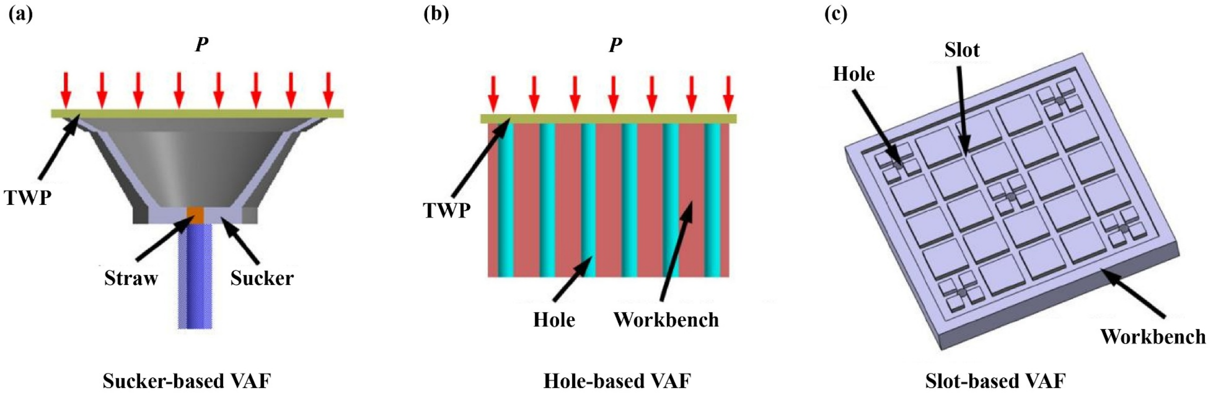


Fig. 7 Vacuum adsorption fixture (VAF) classification based on adsorption unit structure: (a) sucker-based VAF, (b) hole-based VAF, and (c) slot-based VAF. TWP: thin-walled part.

a better adsorption effect, but doing so consumes much time and labor and prolongs the production cycle. The multi-hole VAF is mostly used in the clamping of thin-walled flat parts, and the initial surface error of the workpiece determines the clamping effect. The slot-based VAF is also often used for fixing flat parts and is mostly made of metal. However, some scholars have manufactured slot-based VAFs with rubber and used them in parts processing. They found that the metal slot-based VAF has a better vibration suppression effect than the rubber one [36]. Apart from VAF, electromagnetic suckers are also used for flat parts processing. However, given the limited number of related studies, this section will not present an in-depth discussion of electromagnetic suckers.

3.1.4 Reconfigurable fixture

The concept of RF was proposed in the 1960s and was first applied to the machine tool manufacturing industry [70]. Recently, RF is gradually being used to hold TWPs to reduce the overall costs and lead time and to improve the ability of the fixture to respond to various TWP geometries [71]. Based on the structure and clamping mode, the RF for TWP machining can be divided into ART and MF.

(1) ART

ART was introduced in the “Automation for Drilling, Fastening, Assembly Systems Integration and Tooling” project in Europe before receiving research attention across several companies and institutions, such as SAAB [37], Airbus, BAE, and Leica. ART is a flexible and RF concept for the aircraft industry [38] that combines the modular frame (i.e., box-joint) with locators to clamp aviation TWPs, such as skins and frames (Fig. 8 [39]). The box-joint is a kit comprising steel beams connected by joints that have been patented internationally. These joints utilize contact friction to fasten various beams together, thereby avoiding a tedious welding process and enabling a seamless adjustment of beams. These box-joints are made up of fixing plates placed on either side and are connected by standardized bolts [40]. These joints are not only used to firmly fix beams together but also to conveniently attach locators to the frame. Due to the standardization of all elements, box-joints can be freely matched and combined to build a suitable box-joint frame adapting to the surface geometry. Box-joints mainly comprise a simple box, double box, and squeeze joints. As far as the box joint fixture is concerned, the frame structure and layout of the locators can be reconfigured to respond to variational workpiece geometry. Compared with the traditional welding tooling, ART has a shorter design and manufacturing cycle and lower cost.

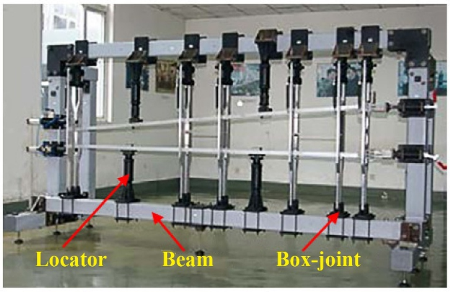


Fig. 8 Schematic diagram of the overall structure of affordable reconfigurable tooling. Reproduced with permission from Ref. [39] from Elsevier.

(2) MF

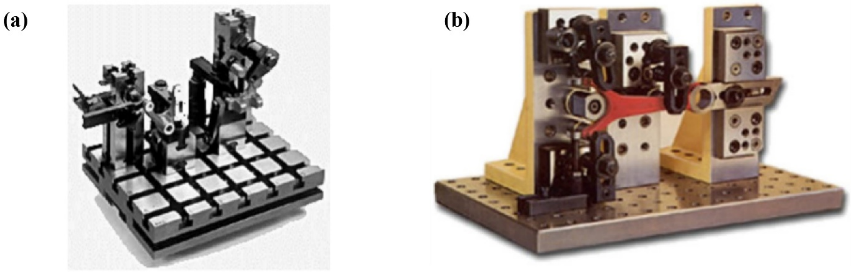
With its strong versatility and reusability, MF is a highly flexible machine tool fixture system made up of a set of standardized modular elements with various shapes, specifications, and usages [72], such as the location module, clamping module, and baseplate module [73]. In industry, MF can be used to hold rigid workpieces or weak rigid TWPs. However, this chapter only discusses the MF for TWPs. MF is widely used in automobile and aeronautical manufacturing fields, such as for holding car bodies during welding.

The MF system is constructed based on workpiece geometry [74] and machining process [75], and the interchangeability and coordination of this system facilitate its reconfiguration, thereby making MF highly flexible to satisfy workholding requirements. These features drastically reduce the investment of capital and time in design and manufacturing and make the MF easier to disassemble, reconfigure, and store. Moreover, to quickly and efficiently build the MF structure, some scholars are attempting to develop a software system for the automated design of fixture layouts [76]. In industry, to meet specific processing needs, the MF is designed to be movable and rotatable [77] in order to quickly adjust its position and posture and to avoid reconfiguration issues. Furthermore, as evidenced in manufacturing practice, MF can be easily matched to most machine tools, hence allowing TWPs to be easily fixed on machine tools. Most commercial MFs are used for the batch and short-run production of TWPs.

Despite the above advantages, MF has several major limitations in production that hinder its application in the manufacturing industry. First, MF requires a high initial investment to ensure sufficient accuracy in standardizing modules and to achieve high coordination and interchangeability. Second, the location accuracy of MF to TWP continuously decreases along with an increasing number of MF elements as a result of the accumulation of assembly error caused by initial manufacturing errors, long-term wear, and operational damage. Third, as the number of MF elements increases, every joint weakens the stiffness of the fixture system. Moreover, poor joints and minor assembly errors can exacerbate the degradation of MF stiffness. Therefore, to obtain reliable and precise joints, MF must be designed with large contact surfaces. Fourth, in the MF design process, for some special and complex TWPs, expert knowledge is required to determine the optimal MF design, which presents a severe challenge to the knowledge and professional ability of designers.

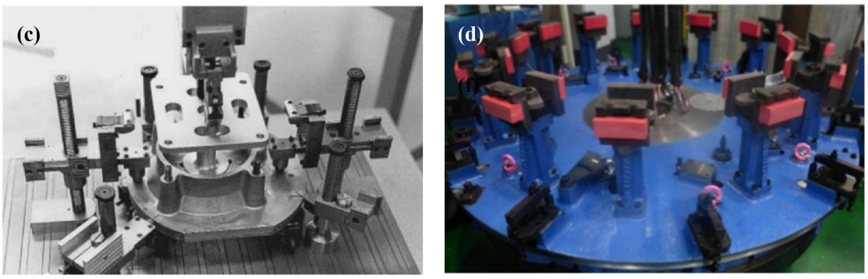
On the basis of their fixation modes, the MFs that are currently being used in the manufacturing industry can be divided into slot-based [41], hole-based [42], automatically adjustable [78], and bespoke baseplate-based MFs [43] (Fig. 9 [42,78–80]). Slot-based MFs have parallel and vertical T-slots on their baseplates and modules, whereas hole-based MFs utilize holes with high position accuracy to fix MF elements. Functionally, these two modes serve the same purpose of holding MF elements and providing configurability. However, for slot-based MFs, the assembly sequence needs to be considered, especially when MF elements are installed on the same row of T-slots [44]. Moreover, automatically adjustable MFs hold various TWPs by using minor adjustments instead of reconfiguration [81], whereas bespoke baseplate-based MFs mainly use the MF elements and a baseplate designed based on the workpiece geometry to hold the TWP.

The layout of MF elements on baseplates or modules is crucial to suppress TWP deformation [82], reduce fixture-induced errors [83], and obtain great surface quality [84]. MF layout optimization aims to determine the best spatial position of MF elements. At present, the main method of layout optimization is to combine finite element analysis (FEA) [85] with optimization algorithms [86] to obtain optimal fixture positions with the best workholding effect



Slot-based MF

Hole-based MF



Automatically adjustable MF

Bespoke baseplate-based MF

Fig. 9 MF classification based on fixation mode: (a) slot-based MF, (b) hole-based MF, (c) automatically adjustable MF, and (d) bespoke baseplate-based MF. MF: modular fixture. Reproduced with permissions from Refs. [42,78–80] from Elsevier and Taylor & Francis.

[87]. Hole- and slot-based MFs are capable of holding different parts through layout reconfiguration, but formulating the layout plan takes much time and labor. The installation and disassembly are also cumbersome processes. By contrast, the automatically adjustable MF can arbitrarily change the position of each adjustable element within a certain range based on the existing structure so as to meet the fixation requirements of workpiece geometry, thereby avoiding the trouble of fixture reconfiguration. However, the limited adjustment range of MF elements significantly weakens the adaptive ability of the automatically adjustable MF to TWP. For the bespoke baseplate-based MF, the baseplate design is based on the structure of TWP, which means that the MF elements have a very limited adjustment range. Therefore, bespoke baseplate-based MF has the lowest flexibility among the three aforementioned MFs. Apart from optimizing the layout, force adjustment is also an important research point for MF [88]. To adjust the clamping force, MF needs to be integrated with a force sensor, an actuator, and a controller. The adaptive adjustment of MF force is a closed-loop process. First, the sensor acquires the force signal between the MF and TWP surface and transmits such signal to the controller. Second, the controller adjusts the clamping force according to the signal analysis results. The closed-loop control of the clamping force is greatly beneficial to the suppression of machining chatter and deformation [89].

3.1.5 Follow-up fixture

FUF is a local fixation mode of the machining area, and the support head follows the tool path throughout the machining process. Compared with conventional fixtures used to hold the entire TWP, FUF is more flexible, is not limited at all by complex surface geometry, and can provide reliable support for the machining area, thereby greatly reducing machining-induced deformation and vibration [90]. FUF can be categorized into MS (Fig. 10(a)), MRS (Fig. 10(b) [48]), and JS (Fig. 10(c) [51]).

MS is a highly efficient support method [45] whose principle (Fig. 10(d)) is to place the machining and support heads on both sides of the workpiece with coincident axes. During machining, the support head moves with the machining head to enhance the local rigidity of the workpiece, thereby suppressing the vibration and deformation caused by cutting loads [91]. MS has received research attention from several institutions. For example, Dufieux Industrie developed an applied an MS system to the machining of large-scale TWPs.

As is shown in Fig. 11, according to the movement mode, the support head can be divided into sliding support head [47] and rolling support head [92]. The internal structure of the sliding support heads (Fig. 11(a) [47]) comprises a port, piston, spring, rod, breathing hole, and universal ball support head. The support force of the universal ball can be adjusted through the electric servo valve to control the cylinder, which in turn is sealed by the port. Due to air compression, the support rod acting on the surface of the TWP can provide a reliable support for machining. During the support process, the breathing hole, spring, and piston work together to enhance the damping properties of sliding support heads. For the rolling support head (Fig. 11(b) [92]), the inner rolling ball makes the support head roll along the TWP surface. The rolling support head does less damage to the

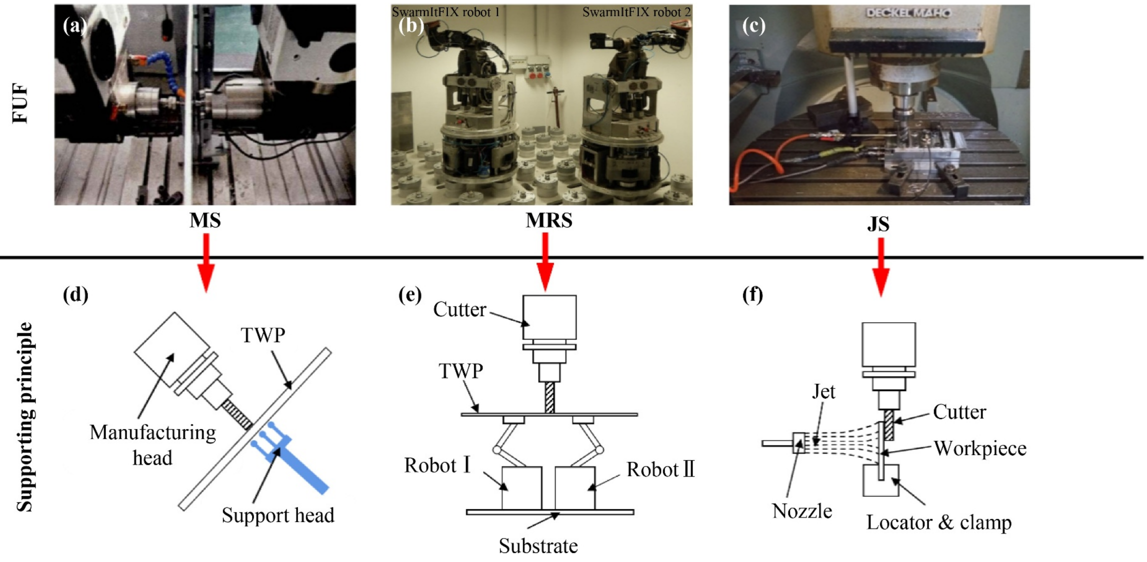


Fig. 10 Follow-up fixture (FUF) classification based on support mode: (a) mirror support (MS), (b) multi-robot system (MRS) [48], and (c) jet support (JS) [51]. The supporting principle of FUF: (d) MS, (e) MRS, and (f) JS. Reproduced with permissions from Refs. [48,51] from Springer Nature.

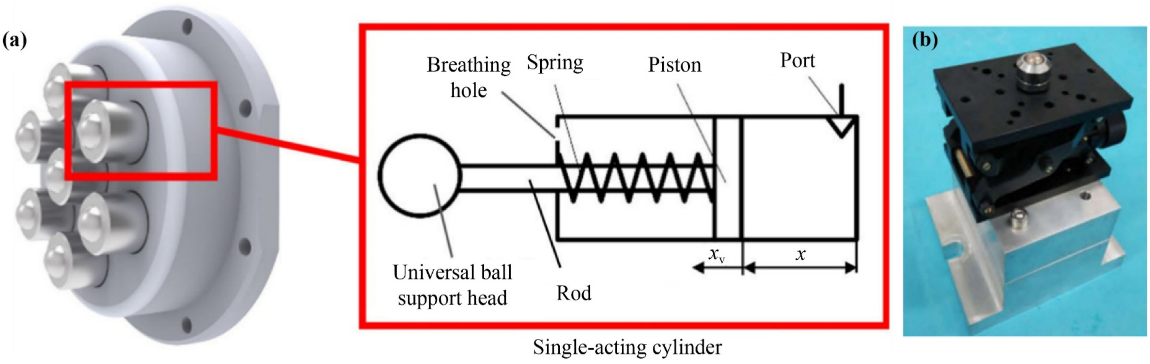


Fig. 11 Classification of support head based on movement mode: (a) sliding support head [47] and (b) rolling support head [92]. Reproduced with permissions from Refs. [47,92] from Springer Nature.

workpiece surface compared with the sliding support head. Given that the multi-point support method has a better supporting effect than single-point support, the two above support heads are mostly designed as multi-point structures.

An MS system with good flexibility and high integration [93] is a green and high effective fixture system [94] that comprises a hydraulic system, pneumatic system, detecting device, and automatic control system. The traditional TWP fixture only considers the fixation of TWP under static condition and ignores the impact of the dynamic load on the machining stability. Compared with traditional fixtures, MS can avoid machining-induced issues by using reliable supports. To effectively suppress vibration and ensure a stable manufacturing process, the motion path of the support head should be carefully planned according to a given tool path to realize stable support for the machining. Meanwhile, the capacity of deformation suppression is also significantly enhanced by the support for the machining load. Apart from planning the motion path of the support head, the optimization of the support position is also necessary to obtain a better support effect and improve the final quality of TWP. Furthermore, enlarging the effective support area is beneficial for maintaining the stability of the machining process. Increasing the number of support points and optimizing their layout are commonly used to expand the support area [46]. A real-time and accurate adjustment of the support force corresponding to the machining load also plays an important role in suppressing chatter and deformation.

Despite its many benefits, MS encounters technical problems and difficulties in production. First, the coordinated and precise control of the support and manufacturing heads is a complex and tedious process wherein the support force and the direction, angle, speed, and distance of the movement need to be continuously adjusted with the processing, and the complex geometry of the TWP surface means a more complicated control process. Second, the sliding support head moving along the tool path can scratch the TWP surface and thus reduce the surface integrity; this phenomenon is due to the fact that the hardness of the support head is higher than that of the TWP surface. While several methods have been proposed to avoid these scratches, such as using a support head made of low stiffness materials or adding a protective layer, they do not provide enough support stiffness for the machining system, and the cutting chips are easily embedded into the support head, thereby ultimately reducing the support effect, accelerating the wear of the support head, and shortening the service time. On the premise of ensuring support stiffness, scratch-free support poses a serious challenge for support head design.

The MRS mainly comprises multiple support robots, a substrate, and auxiliary fixation devices [50], and its working philosophy is to optimize the support state and provide reliable support for the machining process through the coordination of multiple independent and autonomous robots [95]. All robots used for support are mounted on the substrate (Fig. 10(e)). Given that the posture of these robots can be changed arbitrarily, MRS is highly adaptable to the processing, hence explaining its use as a commercial fixture. Moreover, for the MRS system, multiple supports enlarge the effective support area for the machining load, hence improving the steadiness of the manufacturing system [49]. However, the positional relationship among the robots, TWP, and substrate, which directly determines the validity of the support, needs to be investigated in depth by the operator.

Despite its advantages, MRS also has some problems that need to be resolved urgently. Along with an increasing number of controlled objects, the control difficulty of multi-robot supports greatly increases, which poses a huge challenge to the design of the robot control system. Furthermore, given that support robots occupy a larger space than ordinary mechanical fixtures, the number of robots installed on the substrate is strictly limited. In the manufacturing process, when the processing area exceeds the reachable space of robots, the position of these robots on the substrate should be adjusted, which would increase the amount of unnecessary labor input.

JS uses the impact force induced by the momentum and flux of the jet to support the machining load. JS is flexible and stably fluctuates within a certain range to balance part of the cutting force and to simultaneously decrease the vibration acceleration, thereby ultimately reducing the thickness error and surface roughness [51]. Furthermore, due to high flow rate of jet materials, JS can cool down the machining process, which effectively prevents tool wear induced by cutting heat. Given that non-polluting materials, such as water and air, are often used as jet media, JS is considered a green manufacturing technology. As shown in Fig. 10(f), JS comprises a nozzle, jet, cutter, workpiece, and locator/clamp. The momentum and flux of the jet are vital to ensuring the stability and reliability of JS. Results of the experiment show that as the jet moves away from the nozzle, the momentum and flux are reduced constantly. Previous studies also show that the water jet mainly comprises three regions, namely, the inner, coarse mist, and fine mist regions. The inner region is made up of water, the coarse mist region acts as the outer layer and transition, and the fine mist region is the outermost layer. Among these regions, the inner region serves as the main processing support to maintain the final quality of TWPs [52].

3.2 PCM fixture

In 1985, Gandhi and Thompson [95] proposed the use of PCM fixtures, including APCM and PPCM fixtures, for TWPs of different shapes and sizes. According to previous research, the difference between APCM and PPCM is that under excitation, APCM generates a liquid–solid phase change, whereas PPCM does not; however, the PPCM particles are compressed or arranged in a certain pattern (Fig. 12). Most APCMs are thermally-induced materials, such as ice, paraffin, and LMA, whereas most PPCMs include ERF, MRF, and IPBF. Among them, both MRF and IPBF are excited by a magnetic field, whereas ERF uses electricity as the excitation condition. Unlike mechanical fixtures, PCM is a fluid fixture without a specified shape, hence allowing this material to seamlessly and tightly conform to the workpiece surface geometry.

3.2.1 APCM fixture

Most APCM fixtures utilize thermally induced state-change materials, such as LMA, PF, and sand IBF (Fig. 13 [20,57]). These fixtures utilize the liquid–solid phase change of APCM under excitation to clamp TWPs firmly. For APCM fixtures, the clamping of TWPs can be divided into five steps. First, the TWP is located at a specified position in a container. Second, the container is filled with APCM to completely cover the TWP. Third, the liquid–solid phase change of the APCM occurs due to cooling, and the TWP is fixed firmly. Fourth, TWP machining is carried out. Fifth, the APCM is reverted back to a liquid state by heating in order to allow the removal of TWP. The APCM clamping process is shown in Fig. 13(a).

PF can conform to the surface shape of the workpiece, thus supporting TWP machining (Fig. 13(b)). When machining PF-filled TWPs, the vibration amplitude and frequency of the workpiece are significantly reduced [58], hence improving the workpiece surface quality [57]. Nevertheless, given its low support stiffness, PF cannot easily adapt to high-load processing. Using additives can effectively increase the stiffness of PF. Paraffin containing 10% stearic acid has a higher elastic modulus and uniaxial compressive strength compared with pure paraffin. In addition, experiments on the binding force between paraffin and TWP surface reveal that the paraffin containing 10% stearic acid is 8 to 9 times stronger than pure paraffin, and when the mass fraction of stearic acid exceeds 10%, the binding force is steady [59]. Improving the paraffin stiffness and binding force can effectively enhance the clamping ability of TWP processing.

IBF is a green thermally induced state-change fixture (Fig. 13(b)) with good effects on improving the clamping stability of TWP [53]. However, given that ordinary water contains impurity ions such as Ca and Mg, the ice formed by ordinary water has low stiffness, and the impurity ions react with metal and hence corrode the TWP surface. Therefore, deionized water is more suitable for freezing. Moreover, the ice formed from deionized water is more rigid than that formed from ordinary water, and the high rigidity of ice provides a stable holding for TWP and protects the TWP from being cut by burrs or

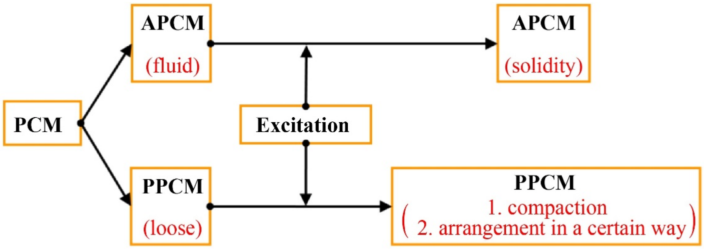
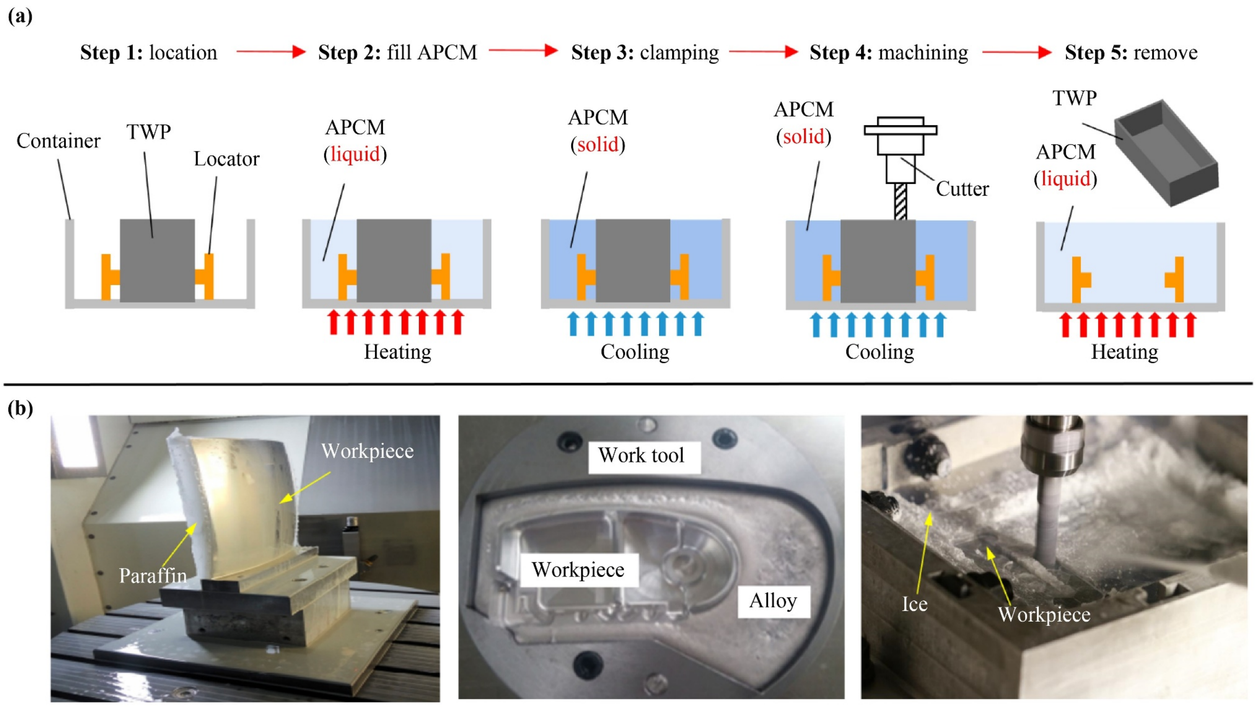


Fig. 12 Differences between APCM and PPCM in terms of phase change properties. APCM: authentic phase change material, PCM: phase change material, PPCM: Pseudo phase change material.



PF **LMA fixture** **IBF**

Fig. 13 (a) APCM clamping process for TWPs and (b) APCM types. APCM: authentic phase change material, TWP: thin-walled part, PF: paraffin fixture, LMA: low-melting alloy, IBF: ice-based fixture. Reproduced with permission from Ref. [20] from Springer Nature.

collapsed edges. An IBF with a melting point of 0 °C can easily melt at room temperature, and the adhesion of ice to TWP is inversely proportional to temperature [54]. Therefore, the melting ice loses its stability and weakens the clamping effect. For IBF, a low temperature environment must be maintained using a cooling system to compensate for thermal disturbances [55]. The liquid nitrogen (LN_2) cooling system, which comprises a vacuum pipe, LN_2 tank, and nozzles, is often used to prevent ice from melting. During the machining process, the nozzle connected to the vacuum pipe and LN_2 tank continuously sprays LN_2 on the machining area to prevent the ice from melting. The clamping effect of IBF depends on the amount of water. Upon reaching saturation levels, increasing the amount of water does not affect the clamping stability of IBF. Water saturation is related to the surface area of the workpiece, and when in contact with the entire workpiece surface, the of water becomes saturated [56]. Therefore, the TWP needs to be immersed in water. IBF shows a good response to the green manufacturing concept of modern industry and is expected to have wide application prospects in the future.

The LMA fixture is appropriate for small- and medium-sized TWPs (Fig. 13(b)). During machining, the rigidity of TWP cannot easily resist the time-varying cutting load, hence leading to cutting deformation in the machining area and reducing the geometric accuracy of TWP. The LMA fixture uses the fluidity of liquid LMA, the combination of solid LMA and the workpiece surface, and the rigidity of solid LMA to suppress the machining-induced deformation. The fluidity enables the liquid LMA to adapt to various shapes of TWP and to fill its structural space. After being solidified, LMA can be combined with the surface of TWP to achieve stable clamping. The rigidity of LMA can provide a uniform and stable support force to the TWP surface, thereby offsetting the cutting load of the tool and ensuring machining accuracy [60]. Nonetheless, when using LMA as the fixture, the impact of alloy on the environment should be fully considered. Despite its low melting point, Pb alloy is harmful to human health and the environment. Therefore, Sn alloys, such as Pb-Sn and Sn-Bi, are often used as LMA material. Moreover, to obtain the optimal clamping effect, the choice of temperature is critical. Wang et al. [20] found that when using LMA with a melting point of 70 °C to clamp TWP, the hardness of LMA below 65 °C is hardly affected by temperature. In other words, the LMA with a melting point of 70 °C can be used within 65 °C for clamping TWP.

Introduced in 1995, the reference free part encapsulation (RFPE) process [61] is a universal fixture process that can solve the traditional problem of location information loss when the fixture device is adjusted [96]. The RFPE process encapsulates the workpiece by freezing it in a low melting point material during machining and transfers the data from one setup to another by refilling and restoring the encapsulation to a known shape after each setup [97,98]. While the RFPE process is yet to be applied in TWP, some scholars have already tested its performance. For instance, Lee et al. [62,63] studied the influence of injection temperature, preheating temperature, cooling rate, pressure, and other factors on RFPE process performance.

APCM has several shortcomings that need to be resolved. First, the thermal energy applied to the phase change creates an undesirable warpage on TWP, especially long ones, due to the transfer of APCM heating into TWP. Moreover, interference factors, such as cutting heat and room temperature, increase the difficulty in maintaining the stability of the temperature field.

3.2.2 PPCM fixture

The PPCM fixture is introduced to address the inevitable defects of the thermally induced phase change fixture. This fixture has several types, including MRF, ERF, IPBF, and dry sand, which require different excitation conditions. The pseudo phase change process of MRF and IPBF [99] can be controlled by a magnetic field, whereas the excitation condition of ERF is an electric field. In addition, the clamping of the workpiece by dry sand is controlled by air pressure.

MRF is a new type of intelligent material that can rapidly achieve a liquid–solid phase change process under a magnetic field (microsecond level), and the stiffness and damping of MRF can be regulated freely [100,101]. Given the above characteristics, many scholars have considered MRF as a TWP fixture (Fig. 14 [102]). First, TWP is located in the container before pouring MRF. Second, under the magnetic field, the MRF undergoes a liquid–solid phase change in the container, hence fixing the TWP in the MRF. The MRF fixture has also been utilized in previous studies. For example, to address the machining-induced vibration of TWP, Liu et al. [64] used MRF to design a flexible fixture device for cantilever TWP (Fig. 14(a)) and carried out machining experiments. They found that increasing the excitation current also increases the natural frequency of TWP and the stiffness of the workpiece-fixture system, thereby enhancing the clamping effect of MRF.

ERF is a mixture of insulating oil and electrorheological particles. The pseudo phase change of ERF occurs when a high voltage is applied to the electrodes. During this process, the particles suspended in ERF gradually generate chains that resemble clusters or columns [103]. This phenomenon reduces the free flow and increases the shear strength in ERF system [104]. ERF also has a fast phase-change time (microsecond level), and the phase change process can be reversed [105]. ERF is viscoelastic under an electric field, and some studies have shown that ERF damping and stiffness increase along with the electric field strength. Moreover, the damping and stiffness induced by the electric field have different effects on the cutting system stability. As can be seen in the process system stabilization diagram, increasing the ERF stiffness can offset the limit lobes toward the higher spindle speed area, whereas increasing the damping can increase the stability limit lobes, which can be viewed as a stable limit increase [106]. Other researchers have designed fixtures by using the pseudo phase change

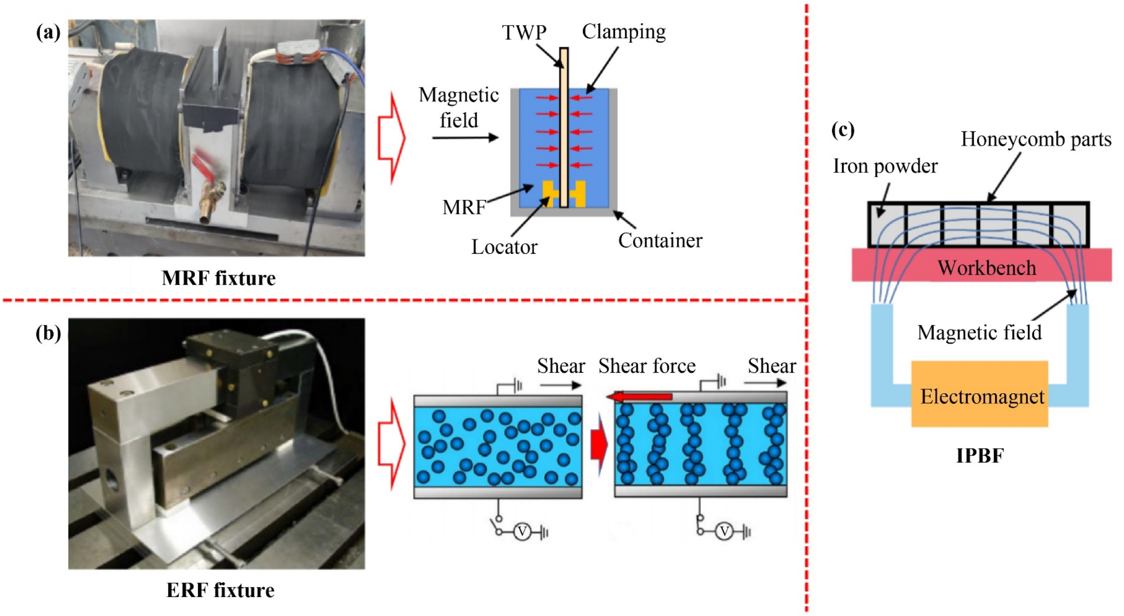


Fig. 14 Structure and clamping principle of the pseudo phase change material fixture: (a) magnetorheological fluid (MRF) fixture, (b) electrorheological fluid (ERF) fixture [102], and (c) iron-powder-based fixture (IPBF). Reproduced with permission from Ref. [102] from Elsevier.

characteristics of ERF (Fig. 14(b) [102]). Following previous research on the structural formation of electric sensitive suspended particles under current and the changes in the mechanical parameters of the medium, Korobko et al. [107] designed an ERF-based device to achieve TWP clamping during the fine turning process. Kakinuma et al. [108,109] designed an electrorheological gel fixture suitable for the micro-milling of workpieces, applied the developed fixture to the micro-grooving of thin glass workpieces, and obtained better machining results. In the designed fixture, the electrorheological gel used is a type of ERF.

However, as TWP fixtures, MRF and ERF show some obvious disadvantages. First, the low stiffness in the solid-state is not sufficient to provide the support required for the high machining load of TWP [110], but some scholars have experimented with the use of compression to enhance the yield strength of MRF and found that using compression can increase the yield strength to 800 kPa [111]. Second, the separation of particles and insulating oil as well as the subsequent sedimentation of particles can cause an uneven particle distribution, which would weaken or even deactivate the pseudo phase change performance of MRF and ERF.

To address these limitations, researchers have developed a particulate fluidized bed (PFB) [112] that can clamp TWP by manipulating the density of bed materials, such as particle or powder materials, during the operation of PFB [113]. By allowing the compressed air to flow into the container, the bed medium acts as a fluid, hence placing the TWP into PFB with minimal resistance. After stopping the airflow, the settlement and compaction of the bed material particle induced by its own gravity enable the TWP to be fixed in the required position. Moreover, to increase the compression force of the PFB particle on TWP, a compaction plate is set in the container port of PFB, which can increase the compaction of particles through a hydraulic clamp and subsequently improve the stiffness of the PFB system [114]. The stiffness of the PFB fixture largely depends on the depth of dry sand in PFB, the immersion depth of TWP, the gravity of dry sand particles, and the pressure of the compaction plate. Some experimental studies have examined the effects of vertical, horizontal, and torsional loads on the rigidity of PFB systems and found that under vertical and horizontal loadings, the stiffness of the PFB system is most affected by immersion depth, whereas the stiffness of the PFB system mainly depends on the section geometry of TWP and the pressing force of the bed material under torsional loading [115]. Although no study on the application of PFB in TWP fixation has been retrieved, the authors believe that this fixture mode can clamp TWP due to its fluidity. Therefore, the authors briefly introduce the principle, usage, and performance of PFB in this paragraph.

Scholars have also proposed an IPBF that mainly comprises a working platform, electromagnet, and iron powder (Fig. 14(c)) [66]. IPBF is a fixture mode that utilizes friction to hold the TWP. Under the iron powder gravity and magnetic field, the friction between the iron powder and workbench and that between the iron powder and TWP surface are remarkably increased to clamp the TWP steadily [116]. Currently, the IPBF is mainly used to fix the honeycomb parts. To improve the clamping quality of workpieces, Liu et al. [117] designed a filling system based on belt transmission that enables the iron powder to fill the cells of honeycomb parts evenly and efficiently, thereby guaranteeing clamping stability. While the IPBF can accomplish a high-performance clamping of TWP [67], several drawbacks need to be considered. First, cutting chips can easily be mixed into iron powder, thereby affecting their reusability, and the excessive impurities in the iron powder reduces the clamping performance. Therefore, when the work is eventually completed, an additional process needs to be performed to separate the iron powder from the impurities [118]. Second, given the semi-open structure of IPBF, iron powder is easily inhaled by operators at work, which will eventually affect their health. Third, the clamping force mainly depends on the amount of iron powder filled into the cells of honeycomb parts, which means that the amount of iron powder will increase along with the workpiece size. Therefore, using IPBF to clamp a large TWP is expensive. These issues greatly hinder the wide usage of IPBF in the manufacturing field.

3.3 Mechanical-PCM composite fixture

The machining vibration and deformation caused by the weak rigidity and strong time-varying characteristics of TWP always accompany the machining process, and sometimes the machining stability of TWP cannot be easily ensured by mechanical or PCM fixture alone. Therefore, scholars have proposed the mechanical-PCM composite fixture to achieve a high-performance clamping of TWP. This composite fixture uses the adaptability of the mechanical fixture to the TWP structural space and clamping requirements to hold the TWP. Meanwhile, the damping, fluidity, and phase change characteristics of PCM strengthen the control ability of the mechanical fixture on the machining process, thereby improving the clamping performance and ultimately suppressing machining-induced problems [26]. At present, the PCM commonly used in the mechanical-PCM composite fixture mainly includes MRF and LMA. Many scholars have explored the mechanical-PCM composite fixture. For instance, de Leonardo et al. [49] developed a multi-robot RF (Fig. 15 [49]) that can be reconfigured according to the machining path to support the TWP machining process. To improve the supporting effect, this fixture is provided with MRF to ensure support stability. Al-Habaibeh et al. [30] designed a clamping system for holding complex-shaped TWPs. In this clamping system, the bottom of the pin is inserted into the container with LMA, and the movement and fixation of the pin are realized by utilizing the liquid–solid phase change properties of LMA. Moreover, the top of the pin is in contact with the TWP surface and hence plays a supporting role in the processing of TWP.

4 Fixture functions

4.1 Basic functions

Location and clamping are the basic functions of fixture and serve as the bases of an accurate, stable, and efficient processing of TWP. With the continuous innovation of fixture technology, various location strategies, and clamping modes are constantly being developed to adapt to the requirements of TWP fixation. This chapter summarizes the methods for the location and clamping of TWP.

4.1.1 Location

The location strategy is constantly being innovated to adapt to the weak rigidity of TWP. The adaptability of the location strategy to TWP determines the position accuracy of TWP and hence affects the machining quality. Some location methods have been proposed to optimally restrict the six DOFs of the workpiece. The “3-2-1” principle is a simple locating scheme that uses only six locators. This mode locates the rigid parts by separately placing three, two, and one locating points on three mutually perpendicular planes to fix the workpieces [119]. However, as the “3-2-1” principle cannot effectively control the gravity-induced deformation of TWP, scholars tend to avoid using this method for locating TWP. The “4-1-1” locating scheme was later proposed, but this locating principle is only suitable for cylindrical parts [120]. Meanwhile, the “4-2-1” locating method uses six points to restrict all DOFs and treats one point as a freely adjustable point [121]. However, this principle cannot easily adapt to TWPs with strong time-varying characteristics and low rigidity. Cai et al. [122] proposed the “*N*-2-1” principle for TWP, which asks for N ($N > 3$) locators on the first datum, whereas the second and third datums have two and one locators, respectively (Fig. 16). The N locators acting on the surface of the TWP can avoid an undesirable deformation. Nevertheless, to obtain an optimal locating effect, the layout of N points warrants further research. The “*N*-2-1” strategy is currently the most widely used method for locating TWP.

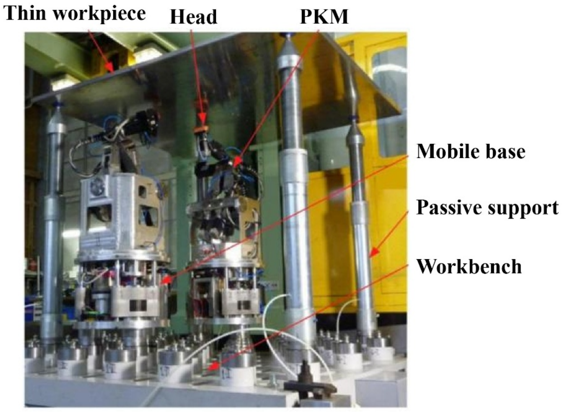


Fig. 15 Mechanical-MRF composite fixture. PKM: parallel kinematic machine. Reproduced with permission from Ref. [49] from Elsevier.

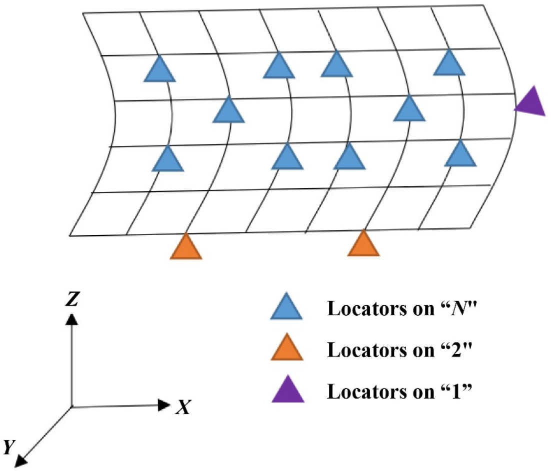


Fig. 16 “*N*-2-1” location strategy for thin-walled part.

The TWP can be located in many ways. The structural features used for locating TWP mainly include surfaces, end faces, and holes. Support rods/pins can adjust the position according to the surface shape of the TWP to achieve location (Fig. 17(a)). In addition, the strong rigid suck utilizes the body of suck to locate the TWP surface (Fig. 17(b)), whereas the weak rigid suck locates the TWP by using the auxiliary support head (Fig. 17(c)). Some TWPs are located by a bespoke mold that is designed based on the geometry of the TWP surface (Fig. 17(d)). Locators are also used to locate TWP (Fig. 17(e)). For the end face, blocks are commonly used for TWP location (Fig. 17(f)). However, the location function of the machine tool platform for the end face of the TWP is often overlooked (Fig. 17(g)). Apart from surfaces and end faces, the hole on TWP is also used to locate TWP in industry practice (Fig. 17(h)).

4.1.2 Clamping

Clamping after location is essential to hold the machined workpiece in the specified position against any manufacturing force and to ensure the position accuracy of TWP.

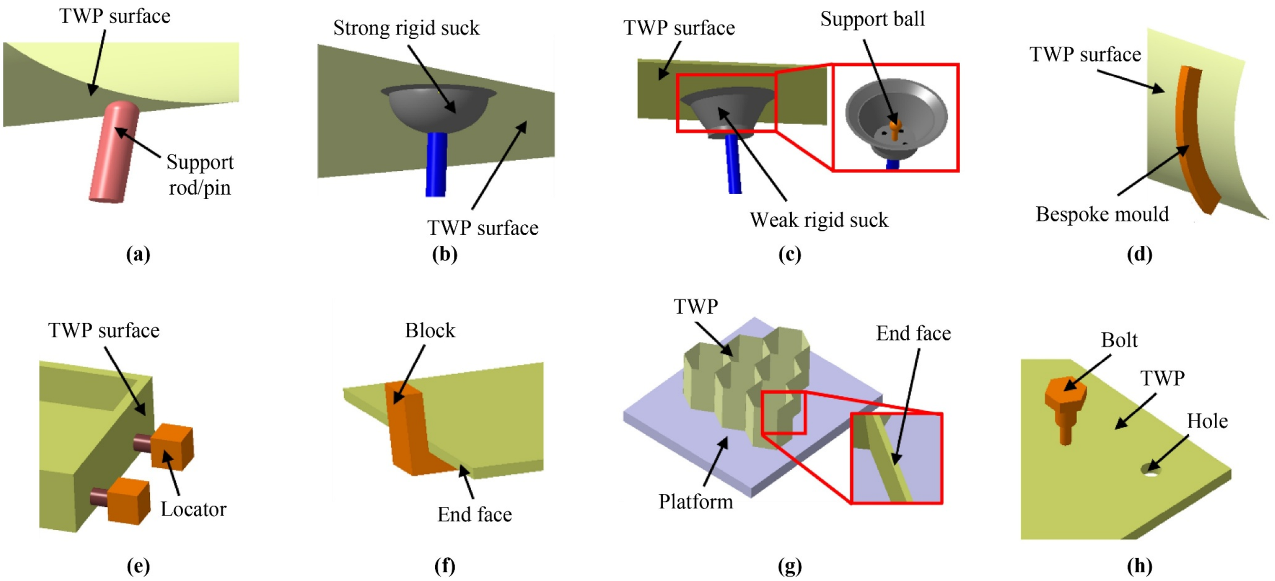


Fig. 17 Common location methods for thin-walled part (TWP) processing: (a) support rod/pin, (b) strong rigid suck, (c) weak rigid suck, (d) bespoke mould, (e) locator, (f) block, (g) platform, and (h) bolting.

The most popular clamping methods currently being used in the industry include clamping devices (Fig. 18(a)), bolts (Fig. 18(b)), VAF (Fig. 18(c)), and PCM fixtures (Fig. 18(d)). Fixing manufactured parts with a clamping device, wherein mechanical force is utilized to clamp the TWP, is the most commonly used method of workholding. However, clamping devices tend to leave some damage on TWPs, including deformation and scratches, particularly at the contact between fixtures and the workpiece surface. VAF is a device that uses air pressure to quickly clamp workpieces. While VAF is less harmful to TWP, the leakage and wear of sucks reduce the stability of this device. Meanwhile, the bolting method uses bolts and holes to fix the TWP in a specified position. However, bolting requires much time for installing and disassembling the bolts, thereby reducing the workholding efficiency. Moreover, when using bolts to locate workpieces, the pretightening force of the bolts cannot be easily controlled, and the choice of pretightening force directly determines the locating effect. The PCM fixture utilizes the phase change feature of PCM to achieve clamping. However, after the TWP machining, the residual PCM on the workpiece surface would require some time to clean up, thereby affecting the TWP production cycle. Recently, Liu et al. [22] proposed a novel and green IBF for TWP that does not require cleaning the workpiece and shows a great application prospect in the manufacturing industry. Generally, clamping devices remain the most popular way of TWP fixation in actual production.

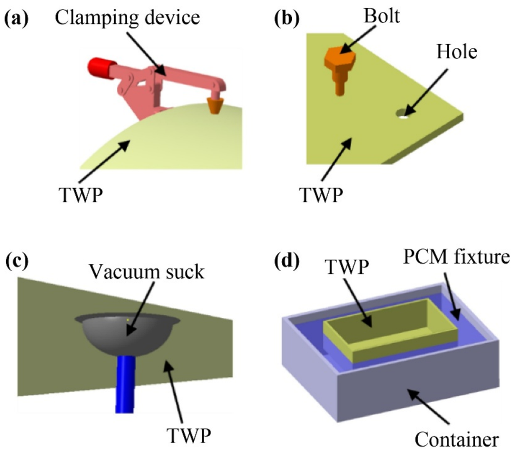


Fig. 18 Schematic diagram of the clamping mode of thin-walled part (TWP): (a) clamping device, (b) bolt, (c) VAF, and (d) PCM fixture. PCM: phase change material, VAF: vacuum adsorption fixture.

4.2 Additional functions

Due to its low rigidity, strong time-varying characteristics, and complex curved shape, the machining process of TWP is accompanied by many issues, including deformation, vibration, low adaptability, and surface damage. Therefore, the fixtures acting on the surface of TWP need to have some additional functions to curb the occurrence of these issues or to reduce the adverse impact of these problems on the processing and final quality of TWP as much as possible. Functional fixtures are preferred for TWP machining in modern industrial applications. On the basis of the issues mentioned above, the functions of fixture for TWP machining include deformation suppression, vibration suppression, flexible protection, and cooling. This chapter analyzes the implementation of these additional functions.

4.2.1 Deformation suppression

TWP deformation is mainly the result of force-thermal coupling and can be classified into force- and thermal-induced deformations [123]. This section only analyzes the former, whereas Section 4.2.5 will discuss the latter. Machining deformation often occurs on TWP due to its low stiffness. Furthermore, the gravity of TWP leads to an undesirable deformation and subsequently result in poor position accuracy. Currently, support is preferred to strengthen the local stiffness of the machining area, offset the machining load [124], and avoid the detrimental impact of the machining load on the geometric accuracy of the workpiece surface [125]. The relationship between support and deformation is illustrated in Fig. 19, where A is the machining point, F_1 and F_2 are the forces of locators and clamps on point A, respectively, F_3 is the force of support devices on point A, F is the machining force on point A, and G is the gravity of TWP on point A. When the TWP is located and clamped (Fig. 19(a)), force-induced deformation does not occur ($F_1 + F_2 = G$). However, when the TWP is machined without the support (Fig. 19(b)), a machining-induced deformation is inevitable ($F_1 + F_2 < F + G$). When the machining zone of TWP is supported (Fig. 19(c)), deformation can be greatly suppressed ($F_1 + F_2 + F_3 = F + G$).

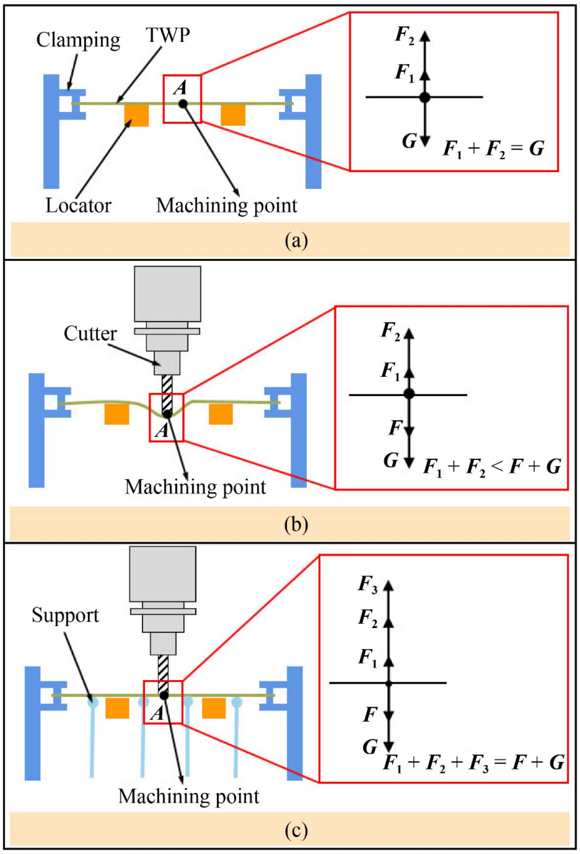


Fig. 19 Schematic diagram of the suppression process of support force on machining deformation: (a) no machining, no support, (b) machining without support, and (c) machining with support.

Apart from support force, the support density for the machining process can also reflect deformation suppression ability, which can be defined as the number of support points per unit area in the machining region. According to the distribution of support points, support methods are generally classified into discrete points (ρ_1) (Fig. 20(a)), array points (ρ_2) (Fig. 20(b)), local multi points (ρ_3) (Fig. 20(c)), and the whole face (ρ_4) (Fig. 20(d)). Functionally, high support density represents strong deformation suppression capability. According to their density, these support methods are sequentially arranged as discrete points < array points < local multi points < whole face ($\rho_1 < \rho_2 < \rho_3 < \rho_4$) (Fig. 20). According to previous research, BF and RF can be known as discrete point schemes, the sucker-based VAF and CF support the machining process by the mode of array points, and FUF is a local multi-point support mode. Moreover, the PPCM and APCM fixtures are capable of supporting the whole face of the TWP.

During the processing, the change in fixture layout is essentially a change in support layout for TWP machining. Therefore, when discussing deformation suppression, this paragraph will use the term "support layout." Some scholars have examined how optimizing the support layout can minimize TWP deformation [126]. Layout optimization is essentially the process of finding an optimal support position where the accuracy [127] and stability of the workpiece-fixture system are the best [128]. A schematic diagram of layout optimization is shown in Fig. 21. FEA is well-suited for simulating and predicting machining deformation induced by impact factors [129] and can provide a great reference for formulating the support layout scheme [130]. By referring to the results of FEA and taking the impact factors related to deformation as constraints [131], the position coordinates of the support points are obtained by using a mathematical model or optimization algorithm [132]. The impact factors of the machining process mainly include cutting force [133], tool path, gravity, and workpiece shape and stiffness distribution [134]. Meanwhile, the mathematical models and algorithms used to optimize the layout of support elements mostly include genetic algorithm (GA) [135], ant colony algorithm (ACA) [136], particle swarm algorithm (PSA) [137], adaptive simulated annealing [138], iterative [139], geometry-based method [140], flower pollination algorithm (FPA) [141], GA and ACA [142], and neural network algorithm (NNA) and GA [143].

In addition to using fixtures to reduce machining deformation, error compensation methods are often used to improve the machining accuracy of TWP. At present, machining error compensation methods are mainly classified into model- and data-driven methods. The

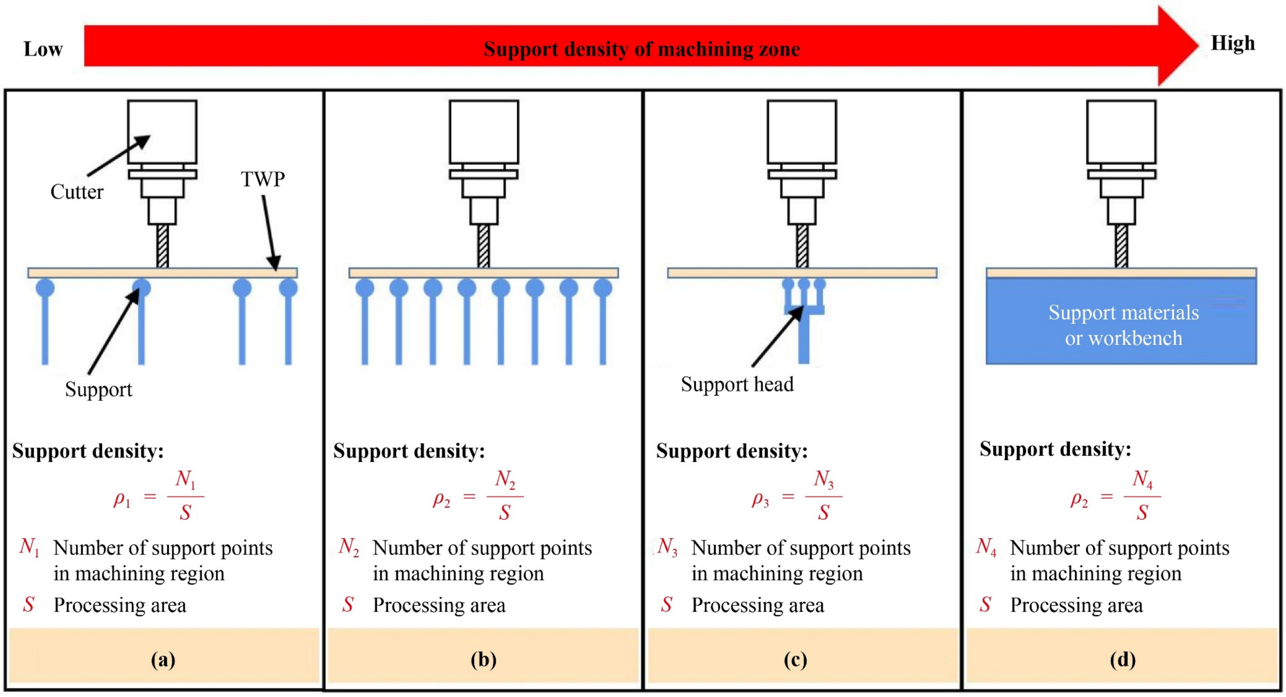


Fig. 20 Schematic diagram of support density: (a) discrete points, (b) array points, (c) local multi points, and (d) whole face. TWP: thin-walled part.

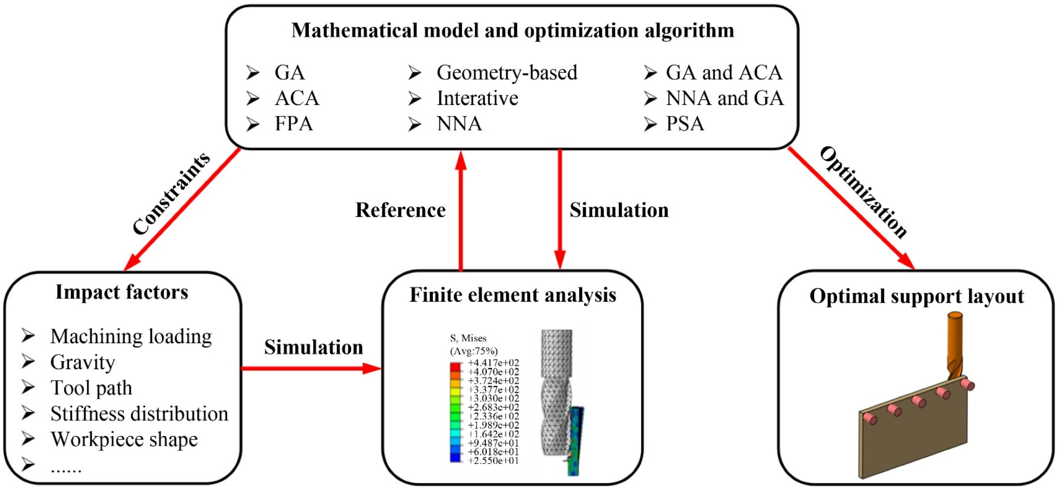


Fig. 21 Schematic diagram of the fixture layout optimization process.

model-based method establishes the analytical [144] or finite element model [145,146] of TWP machining by considering the relationship between the machining variables and the deformation error so as to realize the prediction and compensation of machining error [147]. Ge et al. [148] proposed a rapid deformation computation method based on stiffness matrix reduction and established an iterative cutting force-induced error prediction model by fully taking the tool–workpiece dynamic interaction into consideration. They applied this method to the error compensation of thin-walled aluminum alloy blocks. Apart from the model-based method, the data-driven method measures the actual geometric shape of the TWP after machining by measurement devices [149]. The comprehensive machining error caused by the elastic and plastic deformations of the workpiece can then be directly obtained [150], hence realizing machining error compensation. Fan et al. [151] proposed a data-driven error separation method to compensate for machining error. This method combines the spatial statistical analysis method with an improved simulated annealing-particle swarm optimization algorithm to establish the definite plane and then compensates for the errors by integrating tool path adjustment and cutting parameters optimization.

When obtaining the predicted deformation error, a compensation method plays a key role in ensuring machining accuracy. The common error compensation methods mainly focus on optimizing the cutting parameters [152] or tool path [153]. Essentially, optimizing the cutting parameters and path is a process of obtaining the best combination of cutting parameters that matches the rigidity of the cutting area of the TWP. In other words, under the obtained optimal cutting parameters, the machining deformation error of the part is controlled to the minimum [154]. Si and Wang [155] proposed an iterative compensation strategy and reduced the tool and workpiece deformation-induced surface error by modifying the tool tip position and tool axis orientation. Meanwhile, Wang et al. [156] proposed a cutting process optimization algorithm that can reduce workpiece deformation by optimizing the sequence to remove blocks in cutting operations.

4.2.2 Vibration suppression

Force-induced vibration is a common phenomenon in low-stiffness parts processing that leads to an unstable working condition, poor surface quality [157], and low service performance [158]. Accordingly, scholars are attempting to formulate a strategy for suppressing vibration. The fixture layout design is closely related to the vibration suppression effect of TWP processing. Therefore, optimizing the fixture layout to suppress machining-induced vibration is worth further study. Wan et al. [159] proposed a new analytical model that determines the influence of the fixture layout on the dynamic response of thin-walled multi-framed workpiece throughout the machining process. Their proposed model can predict the dynamic response caused by machining, and on the basis of the prediction results, the fixture layout is improved, and then points *A* and *B* on lines L_1 and L_2, respectively, are taken for dynamic response detection (Fig. 22(a) [159]). Their findings indicate that the improved layout can effectively suppress vibration. Apart from optimizing the fixtures layout, applying a support force suitable for the time-varying machining state can also reduce vibration (Fig. 22(b)). The support force acts on the TWP surface, thereby greatly offsetting the cutting load and suppressing vibration [160]. Obviously, the optimal support force of the fixture is closely related to the cutting load, which directly determines the effect of vibration suppression [161].

In terms of workholding, enhancing the dynamic characteristics of TWP fixtures is essential to ensure a chatter-free machining [162]. Damping is the main approach for reducing the machining vibration of TWP. When damping is applied as a key part of the fixture

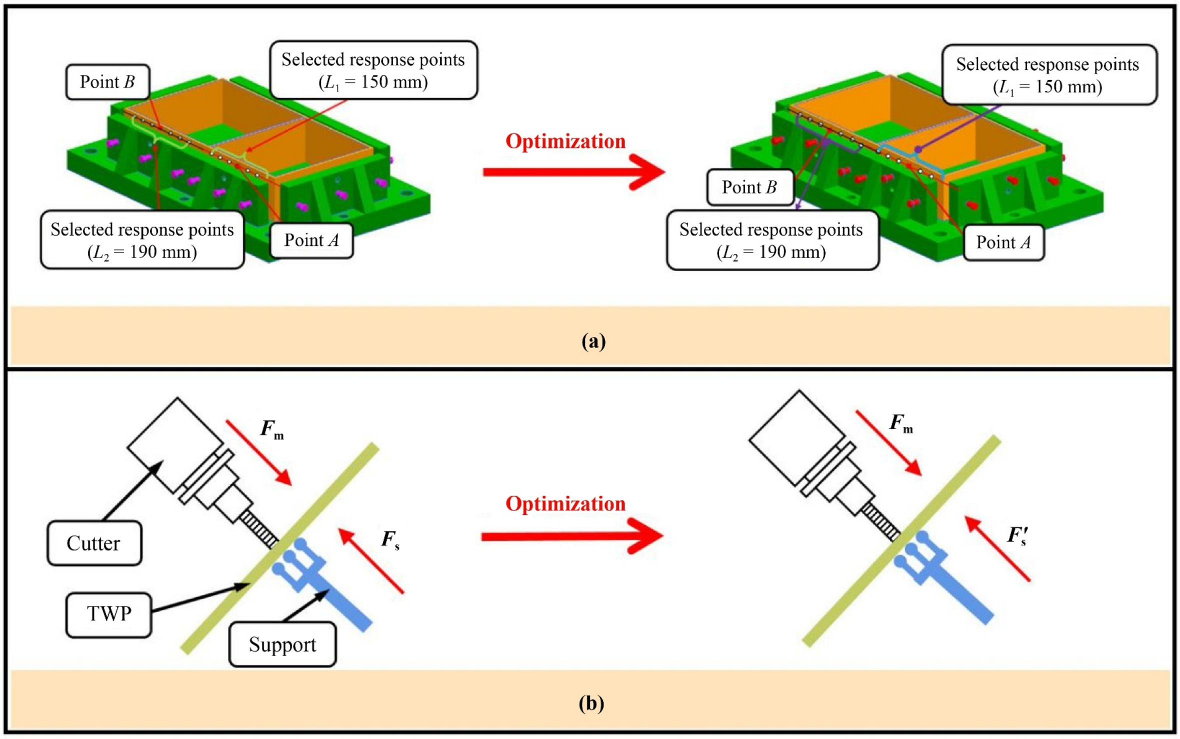


Fig. 22 (a) Optimization of the fixture layout to suppress vibration and (b) optimization of the support force to suppress vibration. Reproduced with permission from Ref. [159] from Elsevier.

system to the machining process, the amplitude of the vibration system will gradually decrease over time due to friction, medium resistance, or other energy consumption. To be in line with the theme of this review, this section only analyzes the damping method from the perspective of fixtures. According to the damping principle, the common damping methods applied to workholding include particle-based damping (PBD) [163] (Fig. 23(a)), tuned mass damping (TMD) [164] (Fig. 23(b) [165]), and eddy current damping (ECD) (Fig. 23(c) [166]). PBD can be used directly to clamp workpieces and absorb chatter, but in industrial applications, this method is often utilized to make dampers. Meanwhile, TMD is usually configured into the fixture system to avoid undesirable vibration. The principle of ECD can be used to make eddy current dampers [167].

PBD. According to the excitation mode, PBD can be classified into ERF and MRF. The following statements take MRF as an example to describe the principle and application of PBD. The magnetic particles in MRF excited by the magnetic field are arranged in chains along the direction of the magnetic field, and MRF changes from liquid to solid in a few milliseconds [65]. During this process, the shear yield stress of MRF sharply increases, thereby increasing the damping force. During machining, the relative movement direction of the workpiece and the side of the container is parallel to the direction of the magnetic field, and the MRF squeezed by the workpiece along the direction of the magnetic field conforms to the extrusion mode of MRF, thereby generating large damping force and rigidity to suppress vibration (Fig. 23(d)).

TMD. The TMD connected to TWP comprises a mass block, spring, and damper. The mechanical energy of vibration is transferred to TMD through the resonance of TWP and TMD in order to suppress vibration. TMD absorbs the vibration from the machining operation to reduce the vibration response at the expense of the large vibration of the mass block [168] (Fig. 23(e)). TMD is mostly installed on fixtures and is in direct contact with the workpiece surface during processing.

ECD. Machining vibration causes the conductors that are in direct or indirect contact with the TWP to move in a non-uniform magnetic field [169], thereby resulting in a relative cutting of magnetic lines and conductors [170] and subsequently inducing an electromotive force that drives the current in conductors or sheets [171]. In the magnetic field, the eddy current in conductors/sheets generates a Lorentz force opposite to the moving velocity direction of TWP to suppress vibration [172] (Fig. 23(f)). Most of the mechanical energy from the vibration is converted into the heat of the eddy current in the conductors [173].

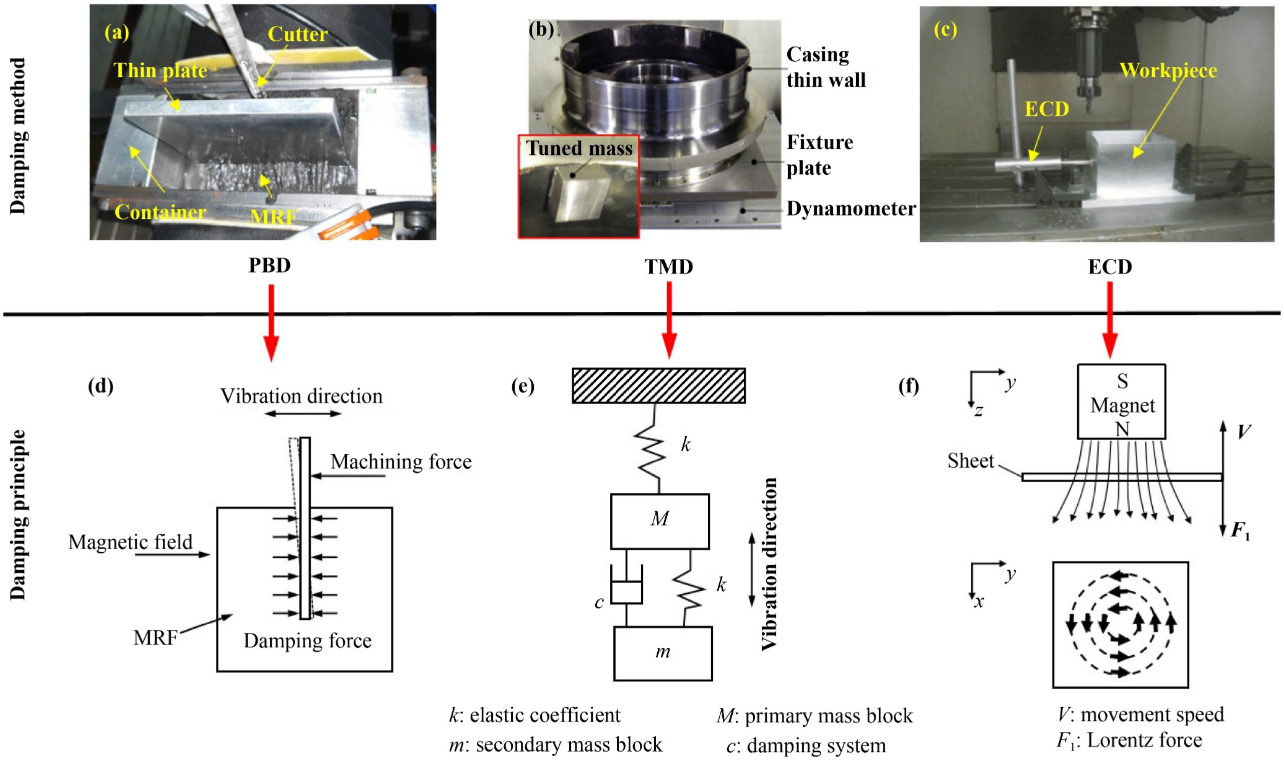


Fig. 23 Damping method for the processing of thin-walled part: (a) particle-based damping (PBD), (b) tuned mass damping (TMD) [165], and (c) eddy current damping (ECD) [166]. Principle of damping: (d) PBD, (e) TMD, and (f) ECD. MRF: magnetorheological fluid, ECD: eddy current damping. Reproduced with permissions from Refs. [165,166] from Elsevier and Taylor & Francis.

4.2.3 Flexible fixture

With the increasing demand for the high-precision machining of TWP, the concept of flexible fixtures for TWP has evolved gradually. Traditionally, flexible fixtures can meet the fixation requirements of TWPs with different shapes and sizes. However, in modern industry, flexible fixtures should not only have an adaptive holding ability for TWP but also conform to the processing to meet people's expectation of a low-cost and high-efficiency fixation of TWP. Adjustable unit is the key feature of flexible fixtures. In terms of the number of adjustable units, traditional BFs almost have no adjustable unit, whereas flexible fixtures have many adjustable units for layout adjustment and planning. A fixture with more adjustable units is highly adaptable to the workpiece geometry and processing. The adaptive layout can be mainly categorized into fluid, fixture unit, and frame layouts.

Fluid layout. The fluid layout (Fig. 24(a) [174]) of the PCM fixture is greatly adaptive to variable geometry. The contact zone between the PCM and TWP surface is free from gaps (Fig. 24(d)) and is much larger than that of mechanical fixtures, thereby ensuring higher clamping stability and more uniform processing support.

Fixture unit layout. The essence of optimizing the fixture unit layout as shown in Fig. 24(b) [32] is to find the optimal fixture unit position where the effect of workholding is the best. Layout optimization is an intricate process in which many affecting factors need to be considered, such as the workpiece geometry, vibration response and deformation, and cutting parameters [175]. Most flexible fixture systems are capable of adjusting the fixture unit layout to adapt to the fixation of TWP with different shapes and sizes (Fig. 24(e)).

Frame layout. The frame layout shown in Fig. 24(c) [39] serves as the carrier of fixtures or the premise of fixture layout. The key task of frame layout is to build an optimal frame structure by considering not only the shapes and sizes of workpieces but also the effect of the frame structure on persons and tool accessibility. The frame layout mostly appears in ART (Fig. 24(f)).

Layout optimization is mostly oriented to the change in the shape and structure of TWP. Moreover, a flexible fixture should be able to respond to real-time changes in the processing. During manufacturing, the cutting force (P_i) is mostly determined by cutting parameters, such as spindle speed and feed rate, and is the most important dynamic signal that constantly changes along with the process. Therefore, fixture-induced force (F_i) should be adjusted adaptively in some working conditions so as to meet the processing requirements (Fig. 25). In controlling fixture-induced force, on the basis of the signal collected by force sensor, the servo system drives the actuators to adjust the fixture force acting on TWP [176]. The fixture-induced force appropriate to TWP processing can minimize the machining deformation [177] and vibration. An adaptive fixture-induced force acts on the other side of the machined side of TWP to offset the time-varying cutting load and weaken the vibration generated by the workpiece excited by the tool during the material removal process. In addition, under the action of the fixture-

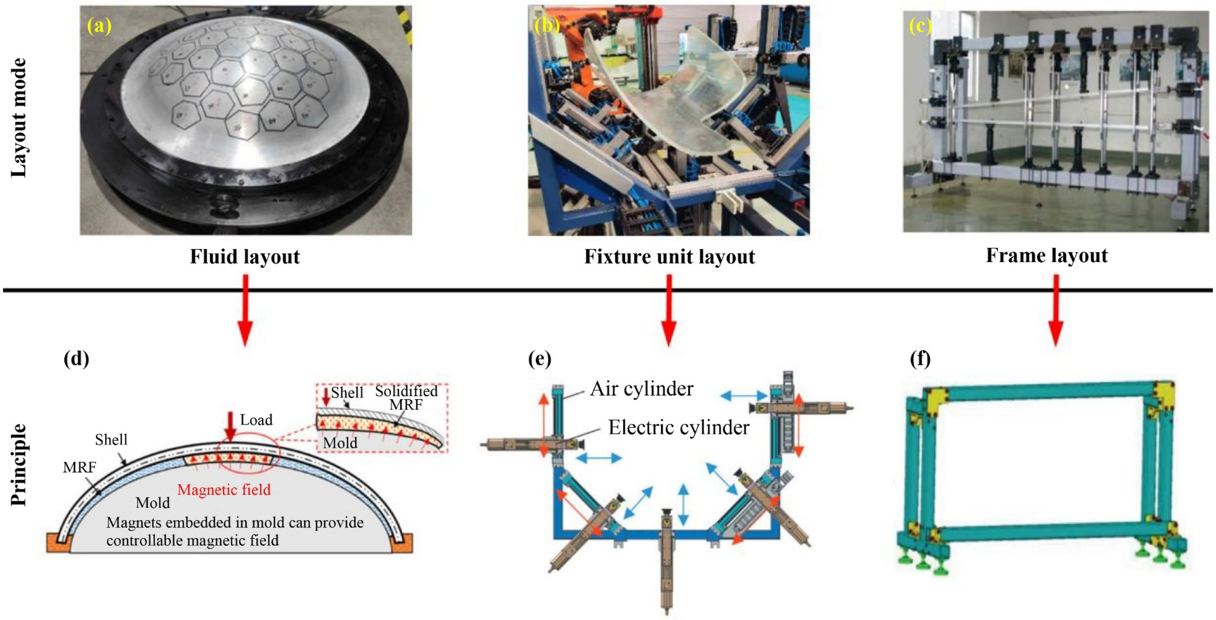


Fig. 24 Fixture layout mode: (a) fluid layout [174], (b) fixture unit layout [32], and (c) frame layout [39]. Principle of fixture layout: (d) fluid layout, (e) fixture unit layout, and (f) frame layout. MRF: magnetorheological fluid. Reproduced with permissions from Refs. [32,39,174] from Elsevier.

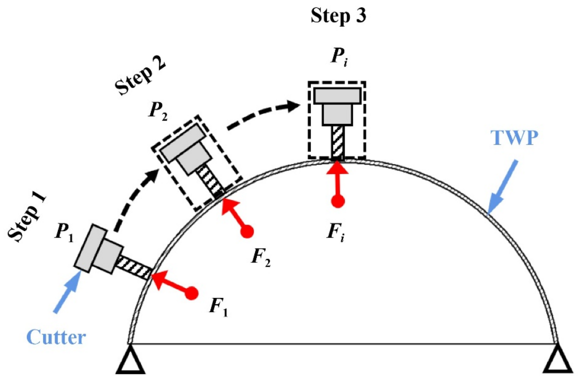


Fig. 25 Adaptive adjustment of fixture-induced force. TWP: thin-walled part.

induced force, the rigidity of the cutting area of TWP is enhanced, thereby suppressing cutting deformation.

Adaptability refers to the ability of the fixture to independently judge and solve the machining problems of TWP, which is the embodiment of fixture intelligence. An intelligent fixture system is a multi-element integrated system. Compared with traditional fixtures, the intelligent fixture system can monitor the dynamic process and obtain dynamic signals from the cutting process [178]. Afterward, on the basis of the acquired dynamic signals, the cutting problems are identified [179], and the response strategy is formulated. The fixture status is then adjusted to suppress machining problems [176,180] and achieve a high-precision machining of TWP [181]. According to the operation process, the intelligent fixture system mainly consists of the following parts (Fig. 26):

- **Perception system**: The perception system mainly collects deformation, vibration, temperature, and other information during the cutting process through multiple sensors configured on the TWP fixture.
- **Autonomous decision-making**: According to the information collected by the perception system, the problems in the cutting process are identified and confirmed, and the best response strategy is formulated.
- **Execution system**: According to the response strategy, the fixture state, such as clamping force and fixture layout, is optimized to suppress machining-induced problems.

4.2.4 Protection

Fixture-induced damage is common in the TWP clamping process. For mechanical fixtures, certain types of damage, such as scratches, indentations, and deformations, often occur on the contact surface between the workpiece and fixture. These damages are often caused by two factors. First, given that the hardness of the fixture is higher than that of the workpiece surface, when machining-induced vibration triggers a relative movement between the workpiece and fixture, the surface of the TWP will be scratched. Second, a large clamping force will introduce certain problems, such as indentation and deformation, thereby forming clamping stress in the workpiece. To avoid these issues, some researchers have installed rubber (Fig. 27(a)) or cotton fabric on the fixture to greatly weaken the contact strength between the fixture and TWP and to subsequently reduce fixture-induced damage to the TWP. Moreover, PCM fixture often corrodes the TWP surface. Therefore, to reduce the damage of PCM to the TWP, some scholars have explored alternative PCMs that do not harm the TWP. One of these PCMs is IBF, which was recently proposed for workholding (Fig. 27(b)). This

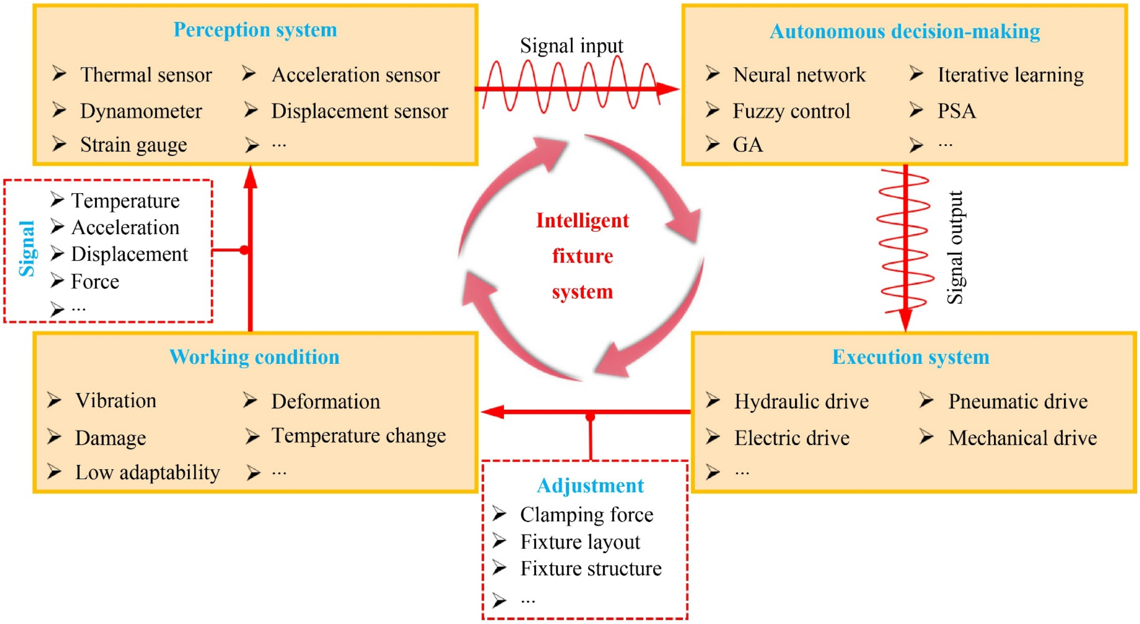


Fig. 26 Intelligent fixture system operation process. PSA: particle swarm algorithm, GA: genetic algorithm.

novel and green fixture is harmless to both operators and workpieces [22].

4.2.5 Cooling

Apart from force-induced deformation, thermally induced deformation [182], including thermal expansion and warping, also presents a significant issue during processing, especially for TWP. Therefore, the machining process is often accompanied by cooling. Cooling not only suppresses thermally induced deformation but also reduces tool wear and extends the service life of the tool. To cool workpieces quickly, workers usually spray coolant liquid in the processing zone, but this liquid is harmful to both the environment and operators, and the coolant liquid remaining on the machine tool and workpiece after processing cannot be easily cleaned up. Cooling TWP with fixtures has recently attracted research attention. During the machining process, the TWP is held by fixtures with a cooling function to effectively reduce the use of cooling media. At present, the fixture modes with a cooling function mainly include IBF (Fig. 28(a) [22]) and JS (Fig. 28(b) [51]). IBF cools down the TWP via thermal conduction at the ice–workpiece interface,

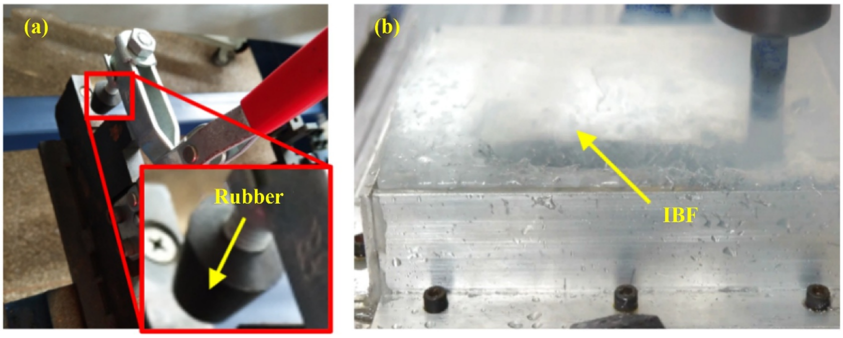


Fig. 27 Clamping protection for thin-walled part: (a) rubber and (b) ice-based fixture (IBF).

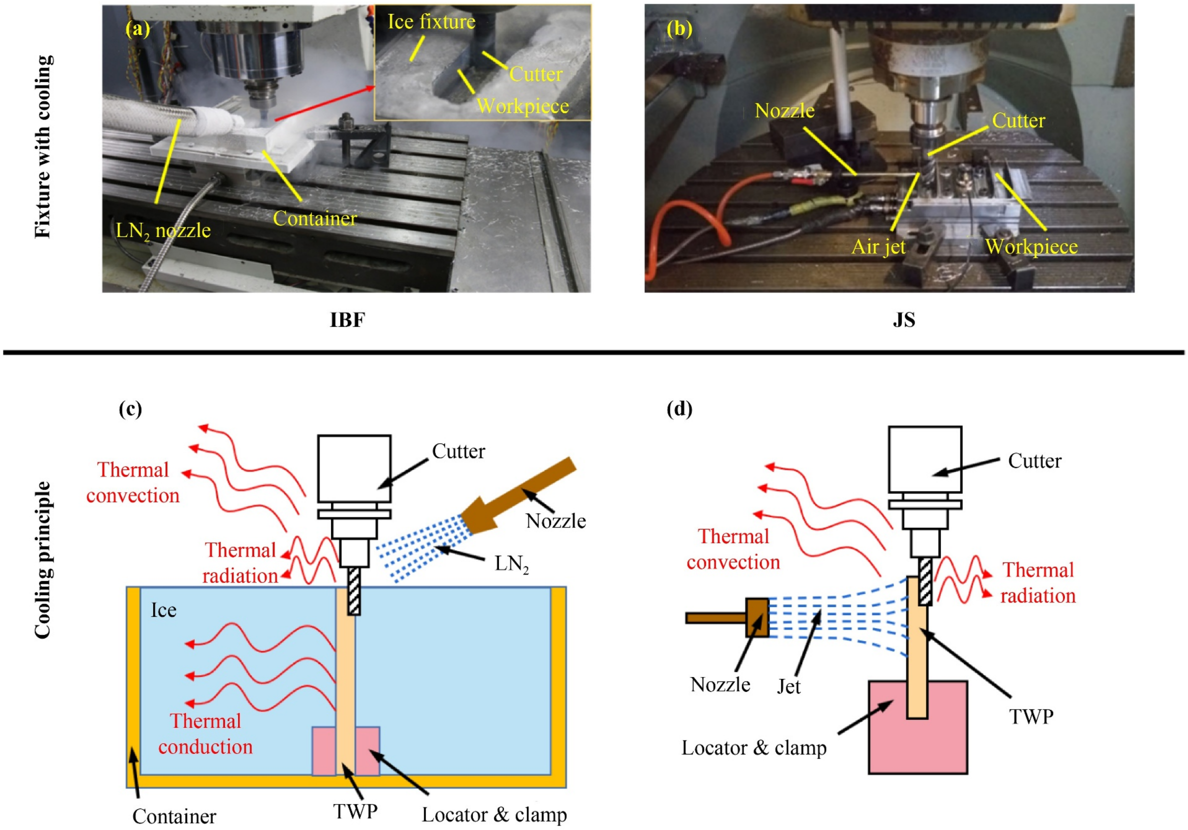


Fig. 28 TWP fixture with a cooling function: (a) ice-based fixture (IBF) [22] and (b) jet support (JS) [51]; cooling principle: (c) IBF and (d) JS. TWP: thin-walled part, LN$_2$: liquid nitrogen. Reproduced with permissions from Refs. [22,51] from Springer Nature.

and the thermal radiation in the machining zone slightly contributes to heat dissipation. Moreover, during the processing, to prevent the ice from melting, LN_2 is often sprayed on the machining zone [22], which can cool down the TWP via thermal convection (Fig. 28(c)). JS uses the impact force generated by the momentum and the flow of jet to support machining load [51]. Air and water are common jet materials. Taking air jet as example, the jet drives the air around the TWP to flow at high speed and then forms thermal convection, thereby accelerating the heat dissipation of the workpiece. Apart from the thermal convection induced by the jet, thermal radiation can also reduce the temperature of the workpiece (Fig. 28(d)). Cooling is a new function of the TWP fixture that represents an innovation in TWP fixture performance.

4.3 Evaluation of fixture functions

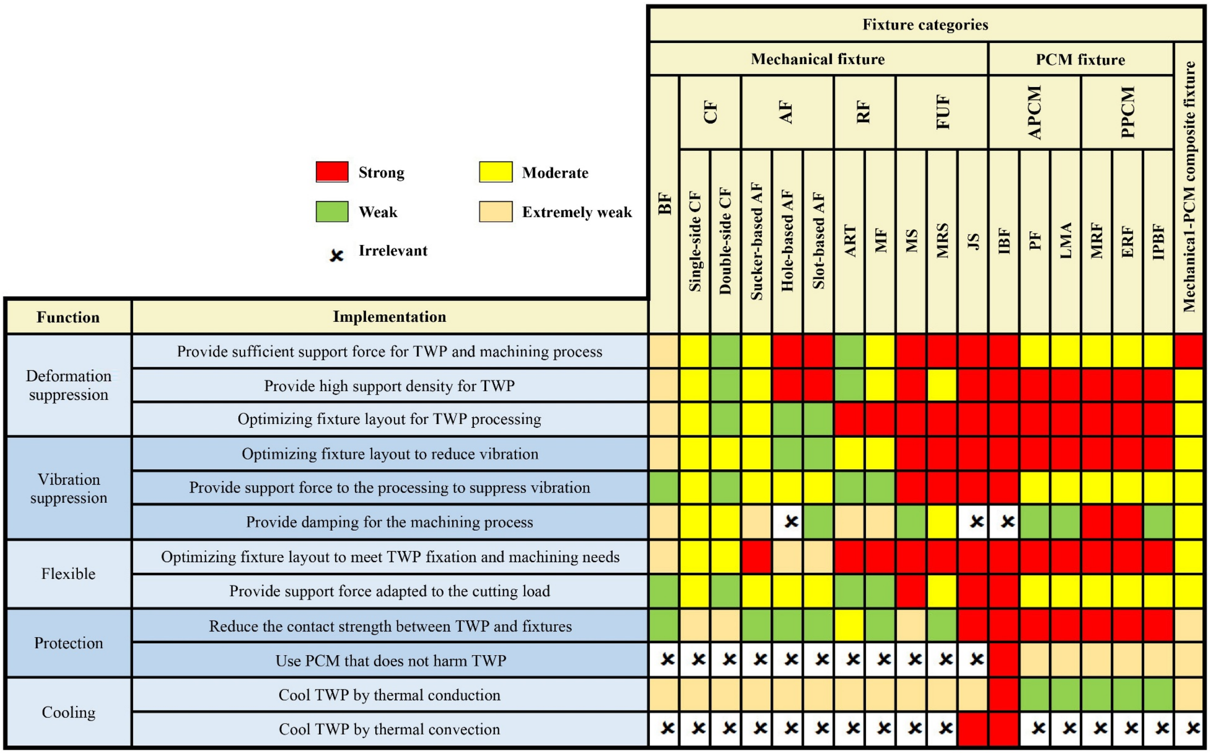
According to the systematic description and analysis of the categories and functions of TWP fixtures in Sections 3 and 4, the functions of various fixtures are evaluated in Fig. 29. These functions are divided into five levels, namely, “strong,” “moderate,” “weak,” “extremely weak,” and “irrelevant.” The implementation of various functions is also described in detail. This evaluation can provide a certain reference for the application of TWP fixtures.

5 Conclusions and future directions

This review begins by highlighting the key role of fixtures in a manufacturing system and then provides a comprehensive summary of the problems that often occur in the clamping and machining process of TWP. According to the workholding requirements, TWP fixtures are redefined from narrow and broad perspectives, and then the functions of these fixtures are expounded. These fixtures are then systematically classified, and their operation mode, structure, and functional characteristics are clearly described. The function categories of TWP fixtures are systematically classified, and the functions of various TWP fixtures are evaluated.

With the increasing demand for a high-performance manufacturing of TWP, as key components of manufacturing systems, TWP fixtures need to be constantly explored and innovated to improve the quality of manufactured parts in a directly or indirectly impactful way. Future research on TWP fixtures should need to consider the following aspects:

- Establishing a dynamic model suitable for strong time-varying conditions is extremely important for understanding the real-time state of the cutting process of the fixture-TWP-cutter system. This dynamic model can clearly express the state characteristics of the machining process in real time and provide some guidance in determining the optimal design of the fixture layout, structure, and clamping method.



🟥 Strong
🟨 Moderate
🟩 Weak
🟧 Extremely weak
✗ Irrelevant

		Fixture categories																	
		Mechanical fixture											PCM fixture						Mechanical-PCM composite fixture
		BF	CF		AF			RF		FUF			APCM			PPCM			
Function	Implementation		Single-side CF	Double-side CF	Sucker-based AF	Hole-based AF	Slot-based AF	ART	MF	MS	MRS	JS	IBF	PF	LMA	MRF	ERF	IPBF	
Deformation suppression	Provide sufficient support force for TWP and machining process	🟧	🟨	🟩	🟨	🟥	🟥	🟩	🟨	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟥
	Provide high support density for TWP	🟧	🟨	🟩	🟨	🟥	🟥	🟩	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
	Optimizing fixture layout for TWP processing	🟧	🟨	🟩	🟨	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
Vibration suppression	Optimizing fixture layout to reduce vibration	🟧	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
	Provide support force to the processing to suppress vibration	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨
	Provide damping for the machining process	🟧	🟨	🟨	🟧	✗	🟩	🟧	🟧	🟩	🟨	✗	✗	🟩	🟩	🟥	🟥	🟩	🟨
Flexible	Optimizing fixture layout to meet TWP fixation and machining needs	🟧	🟨	🟨	🟥	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
	Provide support force adapted to the cutting load	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟥	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨
Protection	Reduce the contact strength between TWP and fixtures	🟩	🟧	🟧	🟩	🟩	🟩	🟨	🟩	🟧	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧
	Use PCM that does not harm TWP	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	🟥	🟧	🟧	🟧	🟧	🟧	🟧
Cooling	Cool TWP by thermal conduction	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟩	🟩	🟩	🟩	🟩	🟧
	Cool TWP by thermal convection	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	🟥	🟥	✗	✗	✗	✗	✗	✗

Fig. 29 Evaluation of thin-walled part (TWP) fixture functions.

- Future research on TWP fixtures should focus on the prediction, perception, decision making, and control of the machining process. By considering the cutting dynamic process prediction model and the extraction and identification of the process signal by a real-time perception system, an online monitoring system for the cutting process is established, and a decision-making system with deep learning capability is developed to drive the actuator of the fixture system to execute the adjustment commands, thereby eliminating the unstable factors that appear or are about to appear. With these technologies, an intelligent control of TWP fixtures for the machining process can be realized.
- TWP fixtures should integrate offline prediction, online monitoring, and independent control into the machine tool system so as to form an intelligent process equipment with machine tools. In this way, an intelligent integrated manufacturing of TWP can be realized.

Nomenclature

ACA	Ant colony algorithm
AF	Adsorption fixture
APCM	Authentic phase change material
ART	Affordable reconfigurable tooling
BF	Bespoke fixture
CF	Conformable fixture
DOF	Degree of freedom
ECD	Eddy current damping
ERF	Electrorheological fluid
FEA	Finite element analysis
FMSF	Flexible multi-point support fixture
FPA	Flower pollination algorithm
FUF	Follow-up fixture
GA	Genetic algorithm
IBF	Ice-based fixture
IPBF	Iron-powder-based fixture
JS	Jet support
LMA	Low-melting alloy
LN_2	Liquid nitrogen
MF	Modular fixture
MRF	Magnetorheological fluid
MRS	Multi-robot system
MS	Mirror support
NNA	Neural network algorithm
PBD	Particle-based damping
PCM	Phase change material
PF	Paraffin fixture
PFB	Particulate fluidized bed
PPCM	Pseudo phase change material
PSA	Particle swarm algorithm
RF	Reconfigurable fixture
RFPE	Reference free part encapsulation
TMD	Tuned mass damping
TWP	Thin-walled part
VAF	Vacuum adsorption fixture

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