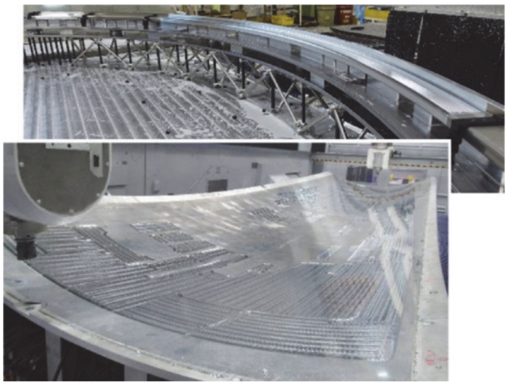
Realizing Lighter Aircraft Parts to Reduce Environmental Impact: Change Manufacturing Process from Chemical-milling to High-precision Machining



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The use of chemical milling for weight reduction in aircraft aluminum parts, such as skins and frames, has an environmental impact issue, and needs to be eliminated. Therefore, Mitsubishi Heavy Industries, Ltd. has developed a new environmentally friendly high-precision machining method to eliminate chemical milling. This developed machining method was first implemented to the Boeing 777X series, which has been produced since 2017. For the latest cargo aircraft, the 777-8F, the transition to this machining method has been fully completed. This report describes the MAG machining developed to realize sustainable aircraft manufacturing and its effects.

1. Introduction

The number of commercial aircraft units produced since 2020 recorded a significant decline due to the impact of COVID-19. However, as passenger demand has recovered alongside the roll-out of vaccines, aircraft demand is also recovering accordingly and is projected to grow even more robustly in the medium to long term [(1)].

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) believes that its commercial aviation business must offer more attractive products than competing suppliers to expand orders from customers during the upcoming demand recovery period. Furthermore, in recent years, initiatives for environmental measures, such as the REACH regulation concerning chemical substance management, have become increasingly important in response to increasing global environmental conservation efforts. Consequently, aircraft production is now required not only to produce attractive products but also to implement further environmental measures and achieve greater results than ever before.

As a Tier 1 supplier to Boeing, MHI is responsible for producing the rear fuselage of the world's largest twin-engine aircraft, the 777X. For its sheet metal parts like aluminum alloy outer panels (skins) and circumferential structural members (frames), which are important core components, chemical milling, a process of immersing parts in a strong alkaline solution to dissolve and mill the material surface, has been used to reduce the weight. While this method has a number of proven results and high reliability for pocket thickness accuracy, it has issues with its high environmental impact due to the disposal of large volumes of chemical waste liquid and its significant amount of ancillary work required before and after processing, and thus needed to be phased out. However, sheet metal parts with large variations in dimensional accuracy after forming cannot be machined using conventional machining methods, and there was no effective alternative method.

To resolve these issues, MHI decided to shift to machining process with lower environmental impact and began developing a new technology in 2012. The developed technology was implemented to the skins of the 777-9 passenger aircraft, one of the 777X series aircraft, which started the production in 2017 [(2), (3)], and to the skin as well as the frame of the latest 777-8F cargo aircraft, which started the production in 2025, completing the transition to machining for all parts

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that previously required chemical milling.

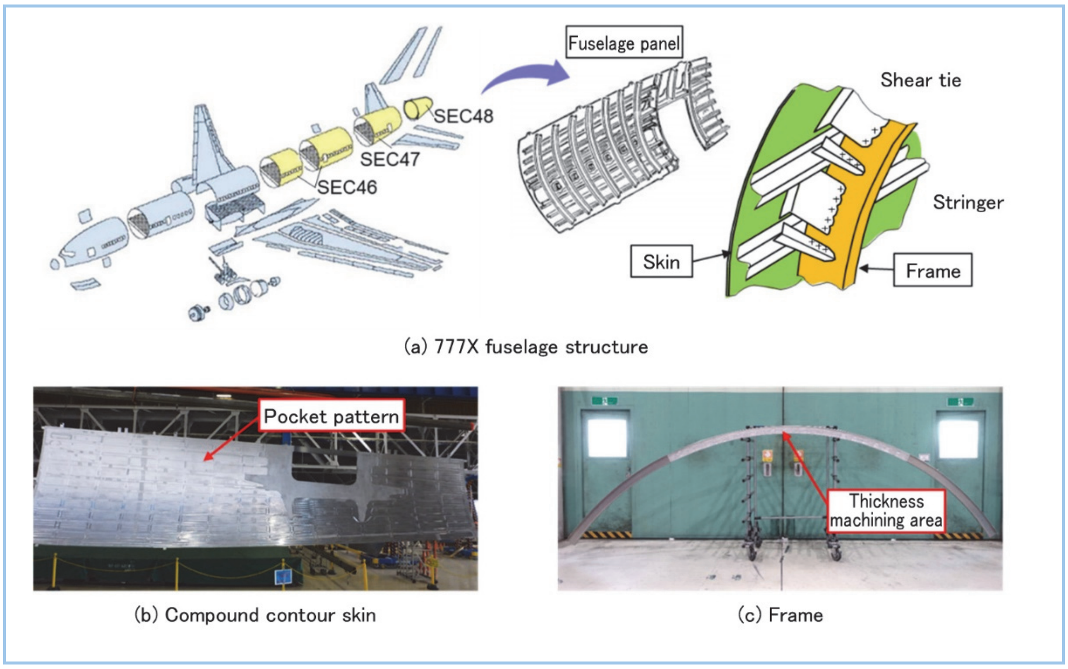
This report presents the Mitsubishi Advanced Green (hereinafter referred to as MAG) machining developed by MHI as an advanced, environmentally friendly high-precision machining method to eliminate chemical milling, and its effects.

2. Overview of target parts

The 777X fuselage has a monocoque structure using high-strength aluminum alloy material. The rear fuselage section, which MHI is responsible for, consists of three main sections (hereafter referred to as SEC) of SEC46, SEC47, and SEC48, as shown in **Figure 1**(a). Each SEC is composed of multiple panels, and the panels of SEC47 and SEC48, in particular, have complex curved surfaces with two-directional curvature changes, known as compound contour. The parts targeted by the MAG machining described in this report are the skins and frames that compose these panels.

The compound contour skin shown in Figure 1(b) is a sheet metal part manufactured using one of the world's largest-class large-scale skin materials, measuring over two meters wide by nine meters long, with a material thickness of several millimeters. Its curvature radius decreases toward the rear section, and the forming process uses a stretch forming machine and die. The inner surface of the formed skin requires pocketing in multiple locations to reduce weight, in accordance with the connection points to structural members such as the frame.

The frame shown in Figure 1(c) is a large sheet metal part, with a maximum length of approximately six meters, formed in a shape with a complex cross-section and a longitudinal contour from a coiled sheet material. It has a Z-shaped cross-section to enhance the rigidity, and is manufactured by roll-forming into the Z-section and a rough circumferential contour shape, followed by stretch forming as needed to achieve the final contour shape. As with the skin, the frame also requires pocketing for weight reduction, necessitating thickness reduction along the steep Z-shaped cross-sectional changes.



(a) 777X fuselage structure
(b) Compound contour skin
(c) Frame

Figure 1 777X fuselage structure and appearance of MAG-machined compound contour skin and frame

3. Issues of chemical milling and their solution

Chemical milling is a method that was devised in 1953 and has been commonly used by aircraft manufacturers worldwide ever since [4]. **Figure 2** shows the chemical milling process and the appearance of the skin during multiple times of etching. The process involves forming a thin sheet into a complex shape through sheet metal working, followed by (1) alkaline cleaning to enhance the adhesion of the maskant, (2) applying the maskant to shield non-processed areas from etching, (3) laser scribing to cut into the maskant along the processing pattern, and (4) pocketing by etching with a strong alkaline solution to dissolve the metal. A pocket shape with multiple steps is processed by etching several times while removing the maskant only from the areas to be etched using the cuts made during (3) scribing.

The advantages of chemical milling include the ability to process complex shapes by repeating the operations of removing the maskant only from the surfaces requiring thickness reduction to expose the surfaces to be processed and immersing them in an alkaline solution for a certain period, and the ability to achieve stable, high-precision processing over a wide area in a single process regardless of shape since the thickness accuracy can be controlled by the immersion period in the alkaline solution.

On the other hand, chemical milling has environmental issues: the products generated by disposing of strong alkaline solution after use and by etching have a high environmental impact and require significant disposal costs, and it is a high-temperature process that uses large amounts of energy in a gas-fired boiler, resulting in high CO_2 emissions. Furthermore, constraints related to equipment, such as large chemical milling tanks and large laser scribing machines, limit the number of parts that can be processed at one time. Consequently, the processing lead time for parts becomes long, making it difficult to supply parts to customers in a timely manner, especially for emergency replacement parts.

The transition from chemical milling to high-precision machining offers significant benefits for aircraft OEMs and airline customers, enabling the timely supply of lightweight, high-precision, high-value-added parts using production lines with low environmental impact. However, to achieve this, it is necessary to perform high-precision machining of sheet metal parts that have large dimensional accuracy variations and complex shapes. As such, to resolve this issue of conflicting requirements, MHI undertook various developments, including new cutting tools, high-precision shape measurement technology, and compensation technology based on measurement results, and has developed a high-precision machining method (MAG machining) that combines these developments at a high level, putting it into practical use. The following chapters outline the technologies developed for the machining of skins and frames.

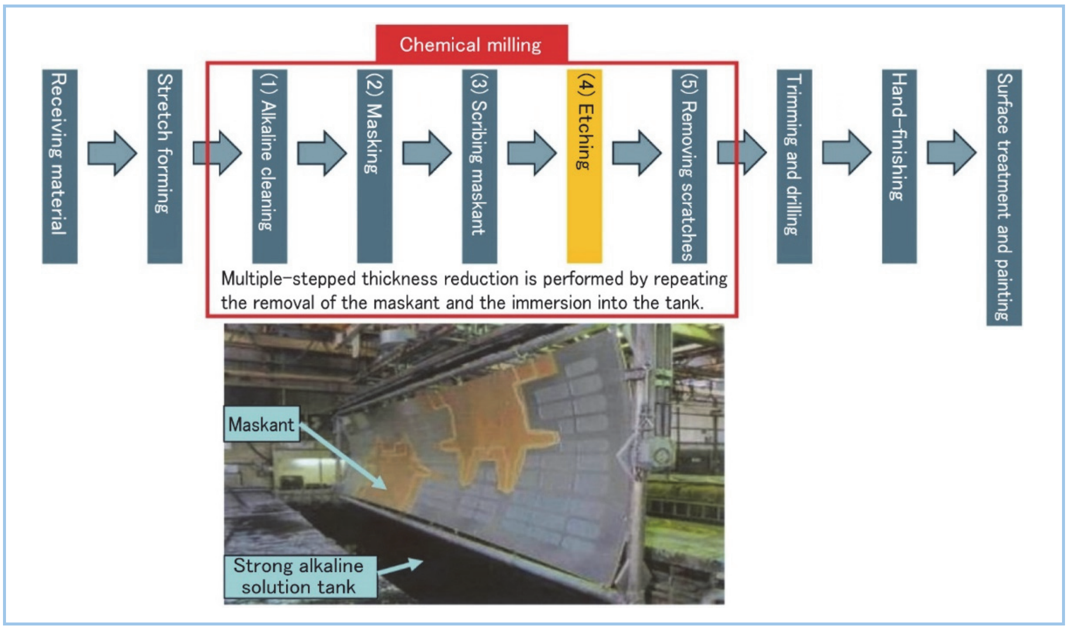


Figure 2　Chemical milling process and appearance of skin being processed

4. Development of skin MAG machining

4.1 Overview of skin MAG machining and issues in its development

Compound contour skins have pockets on the entire surface. These pockets have complex shapes and various thickness patterns in accordance with the parts to be assembled there. The pockets may be located on a kink on the sharp contour shape and near taper shape in thickness transition area, as shown in **Figure 3**. In addition, fillet shape must be needed around the pocket periphery to reduce fatigue strength.

In the skin MAG machining process, a stretch-formed compound contour skin is loaded to a machining fixture with a vacuum equipment fabricated for each shape, holding it in place via vacuum suction, and then placing it into a large vertical 5-axis NC machining center to perform high-precision pocketing, drilling, and peripheral trimming in a single setup without clamp change.

To establish this machining method, two major issues had to be overcome. The first was that although the pocket shape to be machined had a complex compound curved surface, an extremely high surface finish of one-fourth the conventional required surface roughness needed to be obtained by machining to improve fatigue strength due to technological requirements. The second was that the required pocket thickness accuracy of several tens of microns had to be ensured even with a slight difference each fabrication in material property values and sheet metal forming processes.

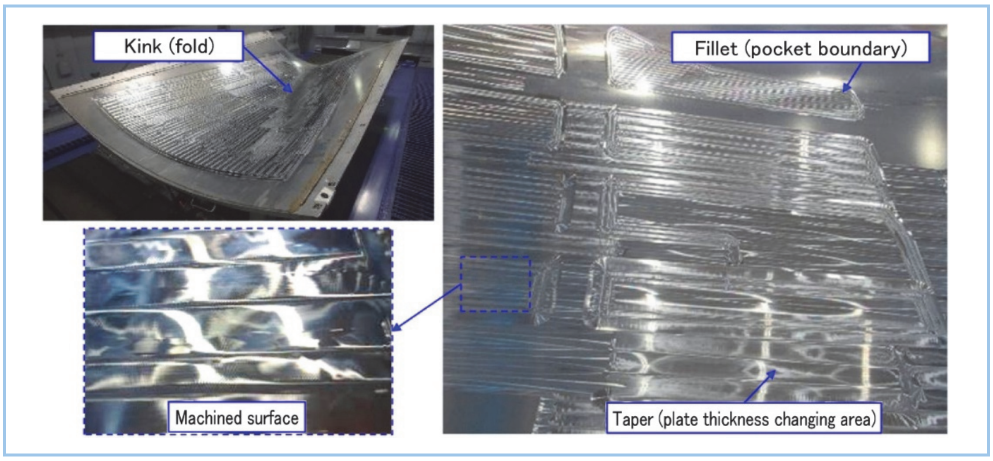


Figure 3 MAG machined surface of compound contour skin and characteristic pocket shape

4.2 Development of large-diameter tool lens cutter

Machining pocket shapes on compound contour surface using the flat bottom face of a standard end mill or milling cutter generates a sawtooth-like step called a hemstitch between machining passes on the machined surface. The maximum value for this hemstitch height (peak to valley height, hereinafter referred to as PV) is specified by the aircraft's required specifications. Reducing the PV requires using smaller diameter tools to reduce the step-over distance (hereinafter referred to as SO) between adjacent passes, resulting in a large number of machining passes and significantly increased machining time. To address this, MHI developed a lens cutter [(5)] having a shape called lens curve on the tool bottom surface, optimized for each compound contour surface shape of the pocket, as shown in **Figure 4**, and achieved a larger tool diameter. This allows the PV to be kept within requirements even on compound contour surfaces while maximizing the SO, thereby reducing machining time. Furthermore, sintered diamond (polycrystalline diamond, hereinafter referred to as PCD) is brazed onto the cutting edge of the lens cutter body for securing high surface roughness requirements after machining. PCD can maintain a sharp cutting edge due to its hardness, enabling machining of large skins measuring nine meters by two meters while ensuring high surface roughness across the entire surface. However, even slight irregularities of a few microns at the PCD tool's cutting edge generated in manufacturing can dramatically degrade the machined surface. Therefore, meticulous production control in the manufacturing is critical.

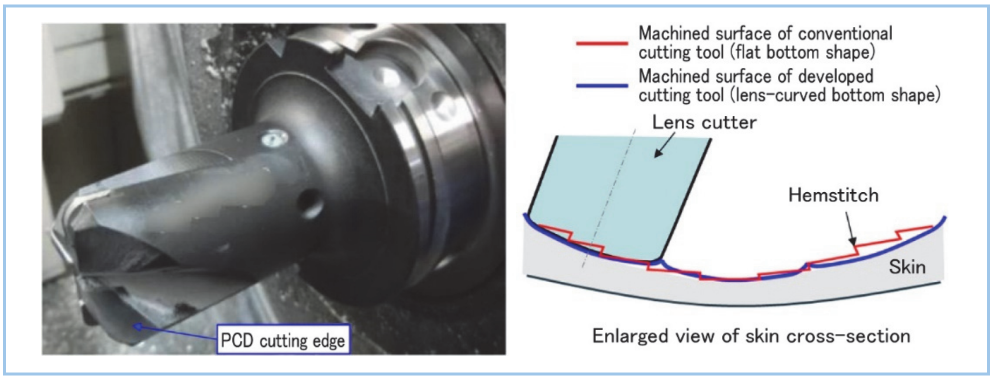


Figure 4 MAG machining lens cutter and characteristic machined surface

4.3 Countermeasures for gaps between fixture and material caused by variation in formed shape

As mentioned above, the greatest problem with the MAG machining is the significant variation in sheet metal parts relative to the required pocket thickness accuracy. Therefore, the standard machining method has conventionally involved rough machining, thickness measurement, and finish machining with corrected cutting depth, i.e., two machining operations. However, even with the use of the lens cutter, performing two machining operations simply doubled the machine-hours since each machining operation took a significant amount of time, making it impossible to ensure sufficient productivity. To reduce this variation, the formed skin shape was predicted using spring-back simulation, and the forming die was compensated taking the prediction into account, thereby enhancing shape accuracy. However, even with this approach, it was insufficient to guarantee pocket thickness accuracy. The cause was presumed to be slight variations in forming accuracy due to subtle changes in material thickness and properties, which affected the gap between the skin and the fixture during each machining operation.

Therefore, an ultrasonic linear-compensation technology, a correction method that measures the skin thickness and the material upper surface position prior to machining after the skin is loaded to the machining fixture to accurately measure the gap between the skin back surface and the fixture, and reflects to cutting depth, was developed (**Figure 5**). A high-precision ultrasonic sensor mounted on the machining head measures the variation in skin thickness, and a touch probe measures the position of the skin upper surface, enabling high-precision measurement of the gap on the back surface. Based on this data, the optimal cutting depth is calculated to automatically generate an NC program with the cutting depth corrected for each designated area, and machining is performed. However, step differences and mismatches caused by the correction amount variations between adjacent areas became problematic. Therefore, a linear-compensation technology was developed to linearly vary the correction amount between adjacent areas, thereby preventing mismatches.

Implementation this ultrasonic linear-compensation technology has eliminated the rough machining process and only finish machining remains, thereby establishing a production system capable of supplying high-quality skins with short lead times.

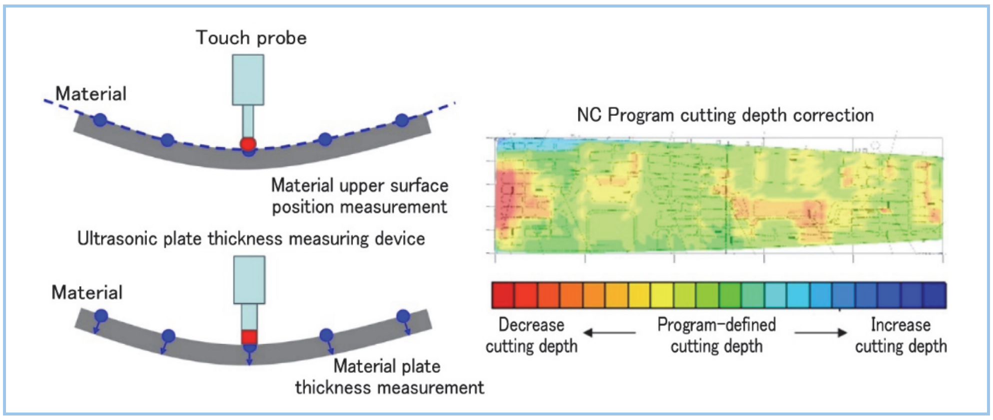


Figure 5 Ultrasonic linear-compensation process for Skin MAG machining

5. Development of frame MAG machining

5.1 Overview of frame MAG machining and issues in its development

Machining of the pocket shape of the frame requires machining of the entire Z-shaped cross-section including the sharp inner and outer bent R sections. In addition, machining is complicated because pad-up shape for mating other parts is designed on the flat surface and fillets for preventing stress concentration are provided on the pocket boundary, as shown in **Figure 6**(a). Furthermore, the dozens of frames all have different cross-sectional shapes, contour shapes, and pocket shapes depending on the airframe shape and stress requirements. Frame shape errors include cross-sectional shape errors, such as those in the flat portions, side portions, and bending portions, and longitudinal shape errors corresponding to the contour shape forming amount, as shown in Figure 6(b).

To produce this frame by machining, it is necessary to control the tool trajectory in the order of microns, following the complex shape errors in the Z-shaped cross-section and the longitudinal direction. Conventional machining can only "cut out" the shape defined by the NC program, making it impossible to "cut into" a predetermined pocket shape on a frame having shape errors. The aforementioned skin MAG machining compensation method alone is not enough to machine frames with steep, three-dimensional shape errors.

Therefore, the frame MAG machining [6], which identifies the three-dimensional shape errors of the entire frame and performs high-speed, high-precision machining while following the tool trajectory in three dimensions according to the identified shape, was developed.

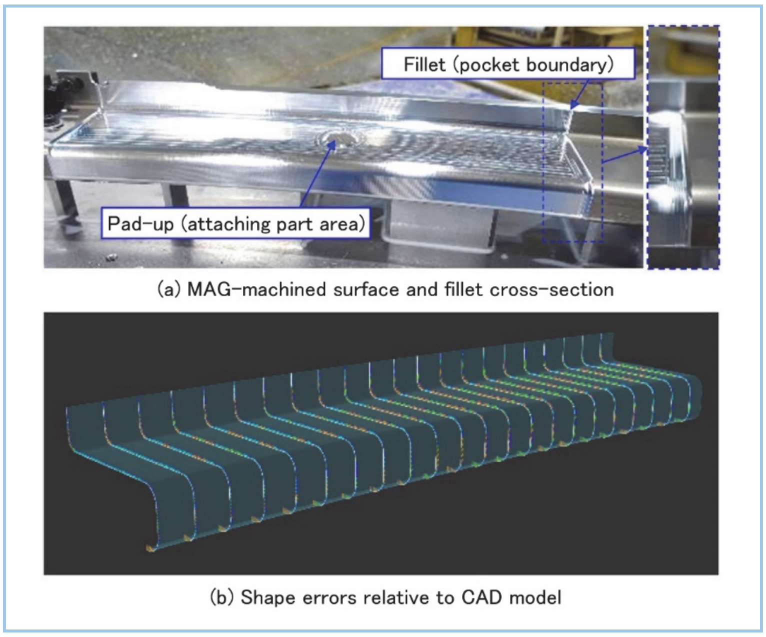


Figure 6 Frame MAG-machined surface and characteristic pocket shape

5.2 Key technologies of frame MAG machining

To realize the frame MAG machining, key technologies such as specialized machining fixtures and cutting tools for frames, as shown in **Figure 7**, were first developed.

Figure 7(a) shows the machining fixture capable for loading a frame with a minimum number of clamps. When loading long, low-rigidity parts like frames, conventional multiple-clamp holding methods cannot sufficiently load the frame to correct its shape within the fixture, and can cause interference of clamps with laser measurement and machining. Therefore, this fixture has a mechanism that can apply circumferential load on both sides. Using this, by pressing the frame against the fixture, high-precision loading to fixture is possible without interference of sensors or tools with the frame during laser measurement or pocket machining.

Next, Figure 7(b) shows an inner radius cutter for machining outside bending shape as an example of specially developed cutting tools. The developed tools have optimized tool shapes to enable the generation of excellent machined surfaces with minimal machining passes, while accounting for errors in the curvature radius of bending shape.

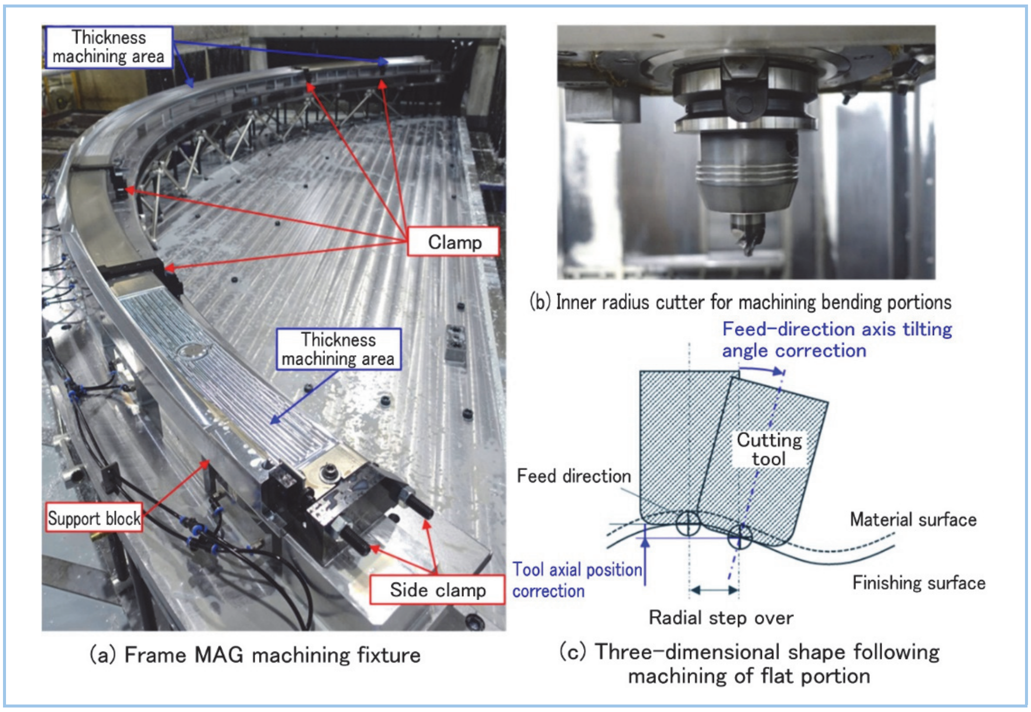


Figure 7 Key technologies of frame MAG machining

5.3 High-precision scanning technology and digital correction technology for realizing three-dimensional shape following machining

Even with the technologies mentioned above, high-speed, high-precision machining cannot be achieved due to shape errors exceeding the pocket thickness tolerance. Therefore, it was essential to develop a three-dimensional shape following machining method capable of accurately capturing the frame shape and adapting to shape changes during each machining operation, one of the most critical technologies for realizing the frame MAG machining.

Figure 7(c) illustrates three-dimensional shape following machining of a flat portion, an example of the three-dimensional shape following machining technology. By not only performing tool axial position control, but also simultaneously controlling the feed-direction tool axis tilting angle to follow the shape of the flat portion, mismatch between radial pitches can be prevented while satisfying the pocket thickness accuracy, enabling the generation of a good machined surface while following the shape.

Figure 8 shows the flow of the frame MAG machining process utilizing the developed high-precision scanning technology for part shapes and digital correction technologies. First, (1) a line laser sensor mounted on the machine tool spindle scans the frame shape at high speed and high precision on the machine tool. Conventional contact measurement method using touch prove has insufficient measurement points, and besides, using a 3D scanner installed outside the machine tool cannot measure a correct positional relationship with the machine coordinate system, resulting in a significant reduction in the measurement accuracy. The developed three-dimensional shape scanning technology enables to measure the high-speed synchronized data between the machine coordinate values and the measured values. Next, (2) the part surface data is generated from the synchronized data scanned from multiple angles, and (3) these surfaces are combined to digitally model, mesh model, which has the actual part shape with high precision in the machine coordinate system. Then, (4) original machining paths are compensated to fit mesh model combined in three dimensionally. Finally, (5) the compensated machining paths are output as a modified NC program, three-dimensional shape following machining became possible.

As this technology enables to construct a digital twin environment for the part to be machined, allowing the generated shape following machining path to be verified through machining simulation. This environment contributed to reduce the lead time significantly for implementation of the three-dimensional shape following machining method.

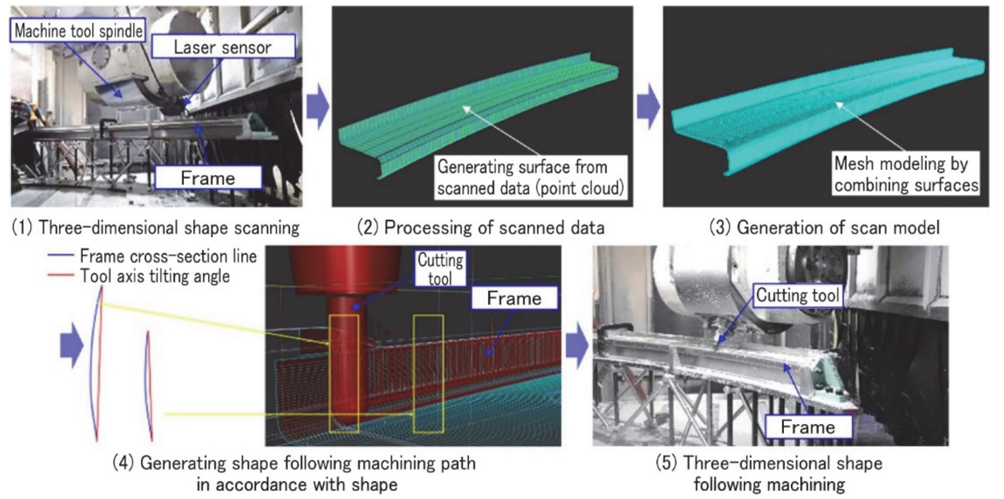


Figure 8 Machining steps for frame MAG machining

6. Conclusion

The newly developed MAG machining implemented MHI's proprietary compensation technology enabled the entire surface of skin and frames with shape variation to be completed machining in one process. This high-efficiency process was able to secure the high-quality surfaces which have less mismatch and reduced surface roughness. Furthermore, the MAG machining enables the machining for pockets, fillets, and tapered shapes, which was impossible with chemical milling. Therefore, it contributes to change the part design with lighter weight and higher fatigue strength required for aircraft fuselages. Moreover, it can simultaneously perform thickness machining and process the high-precision positioning reference holes and component outer peripheral shapes required for the assembly process. This contributes to the automation of assembly processes being developed for high-efficiency aircraft manufacturing.

While composite parts have become mainstream in recent aircraft structures, utilizing this MAG machining enables the proposal of very inexpensive, lighter, and higher-precision skins and frames, even with aluminum structural components, for next-generation aircraft.

The MAG machining has sequentially obtained application approvals from Boeing and achieved full implementation on the 777-8F, which is the latest cargo aircraft in the 777X aircraft series, thereby eliminating the use of strong alkali solution during production. The frame MAG machining technology will subsequently be implemented to the 777-9 passenger aircraft of the 777X series, with a plan to complete the full elimination of strong alkali solution across the entire 777X series by 2026.

Since starting this development in 2012, the skin/frame MAG machining has benefited from the cooperation of various stakeholders over the years. In particular, the authors would like to express sincere gratitude to aT ROBOTICS inc. and CRE Co., Ltd. for their engineering support, and to various cutting tool manufacturers through IDAKA & CO., LTD. for their support in cutting tool development.

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