Dimensional accuracy in quick plastic forming of aluminum alloy using demolding mechanism

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Abstract
This study focuses on quick plastic forming (QFP), product dimensional tolerances, and removal methods. The traditional curled metal shell mold in QFP, has limitations such as long process time and unstable quality. Therefore, this investigation designed a demolding mechanism, in order to improve the process efficiency and dimensional accuracy of QPF, in the manufacture of metal casings. The research results show that the proposed mechanism can significantly decrease the process time, because it replaces most of the operations of specimens movement after forming completely. The shorter process time reduce the die temperature loss during operation, thus also improving the efficiency by eliminating the need to wait for the die to return to its operation temperature. In terms of dimensional tolerance, the tolerance grade of QPF process was determined using the standard deviation, and found to be between IT10 and IT14. This range covers the scope of CNC cutting and stamping processing, indicating that the process has commercial value in the production of metal casings, because the current mainstream manufacturing process of metal casings comprises casting, stamping and CNC machining.

Keywords
Quick plastic forming, cell phone, demolding mechanism, IT tolerance

Date received: 10 July 2020; accepted: 4 May 2021
Handling Editor: James Baldwin

Introduction
Aluminum alloys have attracted considerable attention in recent year due to their possess light mass, high strength, easy recycling, and high corrosion resistance. These useful characteristics of aluminum alloys have led to a major rise in their applications in automotive industry and other engineering fields, such as aerospace industry and telecommunication. However, the widespread applications of wide aluminum alloy sheets are restricted because of their various and complex process technologies, and higher cost compared to steel sheets.¹ Super Plastic Forming (SPF) technology has been successfully employed in the aerospace industry. The slow forming rate of aluminum has been found to be an obstacle to the use of SPF technology in applications, such as manufacturing aluminum car bodies, in the automobile industry, resulting in the developed and adoption of Quick Plastic Forming (QPF).²,³ This QPF methods, also called Hot metal gas forming, has

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successfully produced vast quantities of auto-sheet products. The authors recently applied QPF – Hot metal gas forming to make a shallow rectangular pan with curved peripheral edge in a cycle time of 40 s, with a minimum sheet thickness of 0.6 mm (for smart phone application). Furthermore, some researchers have presented “two-stage gas forming” or “mechanical drawing assisting gas forming” to enhance the production rate and/or thickness uniformity of sheet products.

In all those methods the product is finally obtained by blowing the sheet to fill the single die at a high temperature. The material behaviors is well described by viscoplastic flow rules. The Norton–Hoff law was introduced for the mono-axial creep analysis by Norton, and extended to three-dimensional analysis by Duan. The high temperature, results in zero or negligible spring-back, which is an un-avoidable drawback associated of room-temperature sheet drawing operation. However, ensuring consistent contraction of sheets finished at high temperature when cooling down to room temperature after being extracted from the die is a challenge. Dimension accuracy is an index that has been encountered and studied in 3-D printing manufacturing. Likewise, the QPF needs to bear the same type of dimension accuracy information which has not been available prior to this unique IT (international tolerance) grade study.

A batch of specimens was prepared, and dimensions of each specimens were measured. The spectra of dimension distribution were obtained, and their standard deviation $\sigma$ was calculated. The derived $\sigma$ was converted to an International tolerance (IT) grade and compared with those of other non-traditional processes such as electric discharge machining (EDM), die cast. Additionally, a new mold (demolding mechanism), based on the existing mold design (Shallow rounded rectangular pan and open box) as a reference, and its accuracy and mass production efficiency were measured experimentally.

**Materials and methods**

**Specimens preparation**

The specimens were prepared from two different AA5xxx aluminum alloys – 5052 and 5083, each measuring approximately 1 mm in thickness, and had using three different specimens dimensions and form structure of die. A sample group of 30–40 specimens per die were prepared for dimensional precision analysis, which was the subject of this investigation. The basic equipment required for performing the gas-forming operation to obtain the specimens was, a combined press furnace unit that could provide a stable and uniform high-temperature environment at approximately 400–450°C. Moreover, the press must provide a sufficient clamping force to ensure air-tight contact between the edges of the blank sheet and cover plate. Pressurized gas was stored in a bottled reservoir and made to flow into the compartment enclosed between the cover plate and blank sheet through a port located within the cover plate. The pressurization rate could be controlled step-wise by simply turning a valve by hand. Sufficient clamping force was generated to ensure that the pressurized gas remained trapped without pushing the cover plate or blank sheet while allowing the gas to bulge toward the die-cavity surface, thereby attaining the desired configuration, which was a rectangular box in this case. Figure 1 shows a schematic depiction of relevant die pieces subjected to the established press force.

**Deformation behavior**

In general, materials undergoing the QPF process exhibit viscoplastic deformation, in which the flow stress is
highly sensitive to the strain rate. The QPF process is carried out under isothermal conditions and the stress-strain rate relationship can be described by the phenomenological model:

$$\bar{\sigma} = k\bar{\varepsilon}^m$$

where $\bar{\sigma}$ is the effective flow stress, $k$ is a material constant, $\bar{\varepsilon}$ is the effective strain, $\dot{\varepsilon}$ is the effective strain rate, $m$ is the strain rate sensitivity exponent, and $n$ is the strain hardening exponent. A high value of strain rate sensitivity $m$ is responsible for the superplastic properties of the sheet material, and thus the delay in the localized thinning. The flow stress is obviously affected by the deformation parameters. The peak stress is positively dependent on the strain rate and negatively dependent on the deformation temperature. The flow stress is closely related to the change of the dislocation creep when the metal is deformed.

Superplasticity will correspond to experimental conditions for which grain boundary sliding (GBS) will dominate. Consequently, at higher stresses (and/or at lower temperature), dislocation creep (DC) is expected to be the dominant mechanism. DC involves both glide and climb of dislocations and the lowest between these two mechanisms will control the deformation. An important aspect is that these mechanisms have not the same dependency on the grain size: GBS is promoted by a grain size reduction whereas DC is roughly independent on grain size. For GBS, this grain size sensitivity depends also on the mechanism controlling GBS, volume diffusion or grain boundary diffusion. The mechanism of deformation associated with a high value of the strain rate sensitivity parameter $m$ (i.e. $m \approx 0.5$ or more for GBS whereas $m$ is frequently close to 0.2 for DC) and the value of $m$ is a key in the control of the ductility of a material since the higher the value of $m$, the higher the necking resistance.

**Design and analysis of QPF die**

**Characteristics of rectangular open box die.** Figure 2 shows the die. The main design reference was the shape of an early mobile phone, which has smaller length and width than modern smart phones, but greater deeper. The long axis and short axis directions are bilaterally symmetrical, with a draft angle of 5° to facilitate the removal of the specimens. The specimens dimension were 120 mm × 40 mm × 10 mm.

**Characteristics of shallow rounded rectangular pan die.** Figure 3 shows the die which in design in contrast with the rectangular open-box die, has a middle die in addition to the upper die and lower die. The additional middle die is needed mainly to facilitate the removal of the specimens from the shallow rounded pan die. The specimens dimensions are 151.5 mm × 75.5 mm × 8.77 mm.

**Characteristics of demolding mechanism die.** Figure 4 shows the demolding mechanism die, which differs from the previous die by changing the mold draft angle and increasing the demolding mechanism. The mold draft angle is changed mainly so that the specimens has a vertical wall. While, increasing the demolding mechanism is expected to speed up the rate of production. The specimens dimension is 152.0 mm × 75.4 mm × 9.6 mm. The die is divided into upper and lower molds, which are fixed on the machine. Figure 5 shows the operating procedure.

The design focus is as follows:

(a) Adding a dowel pin can improve the efficiency of assembling the die and reduce the cost of raw material. QPF is a high-temperature process, causing the mold components to have
thermal expansion effects. This investigation found two problems. The first is that the demolding mechanism and groove tolerances are designed for sliding fit tolerances at high temperatures. Since the mold components are assembled at room temperature, the relative gap increases, and determining whether the assembly is in the correct position is impossible. Second, increasing the gap between the demolding mechanism and the groove to avoid the thermal expansion effect increases the material cost due to the increased quantity of sheet material. The dowel pin is designed to avoid these problems.

(b) The demolding mechanism can provide a stable stripping force for the specimens after the process is completed. The specimens after forming is in the groove of the lower mold. Removing the specimens, requires an upward force perpendicular to the lower die surface, while also overcoming, the friction between the sheet and the lower die. The demolding mechanism is designed according to the above requirement, with the upper die fixed and the lower die moving up and down. A flat bearing is designed to contact the sheet metal, and connect it to the upper die. The sliding rod slides with the upper die, and is fixed on the upper rod. The two rods are combined into a pull rod mechanism. When the lower die is lowered beyond the extension range of the demolding mechanism, the ejector rod and the sheet generates an opposite forces, causing the sheet to be demolded.

Measurement method

In order to ensure that the measurements were consistent, the measurement was performed at room temperature using specific measurement fixture is constructed for each specimens shape. The measurement fixture were built using 3D printing technology, and made from plastic material, which significantly reduced the difficulty of fixing the sheet and the potential for human error. Three measurement molds are shows in Figure 6.

The clamping design for the measurement of the rectangular open box is located at the red circle in Figure 6(a). The clamping design for the measurement of the dimension of the shallow rounded rectangular pan is located at the four circles in Figure 6(b). To ensure consistency of points during measurement, the work piece was fixed using a symmetrical clamping design on both sides. The clamping design used for measuring the dimensions of the veridical wall rectangular pan combined the features of both other measuring fixture, and had six clamping points, as shows in Figure 6(c).

The vernier caliper was placed into the groove to fix it and reduce the gap between the caliper and the fixture when measuring it, thereby reducing measurement errors and increasing measurement accuracy. The groove design also made the vernier caliper parallel to the measurement test piece, following the Abbe principle to improve the measurement accuracy. Figure 7 shows the relative measuring position on the test piece. The short side measures three positions (A, B, C), and the long side measures one position (D).

Dimensional tolerance

The International Tolerance Grade (ITG) specifies tolerances with associated manufacturing processes for a given dimension, and indicates the precise an industrial process. ISO 286-1:2010 provides for 20 values for sizes up to 3150 mm, IT01, IT0, IT1 . . . IT18. A lower IT grade number indicates higher precision in the machining process. Measuring require IT01–IT7 is fits require IT7–IT11, and Large Manufacturing Tolerances require IT12–IT18. Geometric dimensioning and tolerance is a system for defining and communicating engineering tolerances. It explicitly describes the nominal geometry and allowable variations for specimens. The IT grading system is widely used in industrial manufacturing.

According to the research of Kitsakis et al. and Islam et al., the IT calculation formula has been modified to better conform to general industrial applications. $T = PC = 6\sigma$ was defined in the study ($\sigma$ represents the standard deviation), where $6\sigma$ provides for a range $\pm 3\sigma$ in normal distribution. From the perspective of normal distribution, a product quality of $\mu \pm 3\sigma$ ($\mu$ = average), denotes a yield of 99.73%, and thus a defect rate of only 0.27%. Calculating the standard deviation requires at least two data, with more
data leading to a calculation closer to the actual value. The calculation formula is as follows:

$$PC = (0.45 \times \sqrt{X} + 0.001X)10^{IT-16}$$

PC: process capability tolerance
X: manufactured dimension, unit: mm
IT: International Tolerance
Results and discussion

Parameter analysis of quick plastic forming process

Process parameters optimization is mainly directed to the die of the demolding mechanism. The parameters discussed in this investigation are lubricant, clamping force, die temperature, preheating time, and forming conditions. The aim is to shorten the forming time and optimize the experimental parameters. Tables 1(a) to (e) present the test results of the specimens. The experimental parameters for tolerance analysis of specimens were no additional lubrication, forming time 60 s, preheat time 60 s, clamping force 15 tons, and die temperature 410°C. Coating the lubricant-graphite on the material before forming can lower the friction between the sheet and the die, and thus improve the demolding effect, also will increase the process time. The effect of lubrication was tested at a die temperature of 410–450°C. Table 1(a) shown the results. While AA5052 must be coated with a lubricant at 450°C for demolding, While AA5083 can be taken out without lubrication at 450°C. The reason is well strength of AA5083 at high temperature, however, it is worth noting that specimens with lubricant at 410°C is broken. The reason needs to be further studied. Gas forming needs to be performed in an airtight cavity. The clamping force principally resists the gas pressure during gas forming. Excessive clamping force thins the test piece at the airtight clamping place, causing specimens fail. Too small force results complete formation. The clamping force was set between 5 and 25 tons. Table 1(b) shown the experimental results. The difference in the appearance of the specimens is difficult to observe visually, and must be judged from the actual measured dimension. For optimal forming effect, the clamping force was found to be 15 tons.

The die temperature is one of the main factors affecting the formation. Table 1(c) show the experimental parameters of different die temperatures in the process. The experimental temperature range was 450–400°C. The die temperature gradually decreases due to other parameters and energy consumption. The die temperature of 450°C caused failure when lubricant was not applied, and the formation dimension was affected by demolding. The dimensions of specimens with die temperature of 430–410°C were within the set tolerances, so the die temperature was selected as 410°C. The small dimension of the specimens with die temperature at 400°C was due to the decrease in temperature and in elongation, requiring increase formation time to improve the specimens. Increasing the formation time increase the production time, so this temperature was not considered. The manufacturing process required formation at high temperature. The specimens must have a preheating time to make the specimens temperature close to the die temperature. This action affects the production time. Table 1(d) shows the experimental results. The preheating time decline with decreasing die temperature. Reducing the die temperature from 450°C to 410°C, reduced the preheating time, without affecting the formation. This result indicates that the preheating time is adjusted according to the die temperature, and the length of the preheating time does not directly affect the forming effect. The forming conditions include pressure and time. Table 1(e) shown the experimental analysis results. The forming time ranged from 80 to 50 s. The maximum forming pressure was 4 MPa, and the pressure base was adjusted in 1 MPa. Gas formed for 20 s or 10 s in each pressure zone. The dimensions of the specimens in the table indicate that the gas pressure to 4 MPa, reduced the forming time to 50 s. The specimens produced by 70 s formation still did not meet the dimension requirements. The formation time was within 50 s at a blowing pressure of 4 MPa, and the dimensions were within the tolerance range. The forming conditions were selected in this experiment to ensure the dimensional stability.

Mechanical properties and microstructure

Type 5083 and 5052 aluminum alloys are commonly used, especially the 5052. Their room and high (450°C) temperature tensile test results are depicted in Figure 8. At room temp., 5083 is much stronger than 5052 and it is commonly acknowledged. Moreover, the former one is also significantly more ductile at high temperature which means 5083 is more suitable for QPF.

In order to better understand the effect of grain on the froming of these aluminum alloys, a microstructure analysis was performed on the forming specimens. The grain structure (i.e. size and shape) was investigated as the grain structure was known to largely influence the overall material response. The specimens were cut along the transverse directions as shows in Figure 9. The specimens were then mechanically polished and etched.
with Graf Sergeant reagent (15.5 ml HNO₃, 0.5 ml HF, 3 g Cr₂O₃, and 84 ml H₂O) to reveal the undeformed grain structure at the “base location” and the deformed grain structure at the “round” and “bottom” regions as depicted in Figure 10. Most of the grains were found to have granular structure at the base and the bottom location (i.e., undeformed grains), while elongated and elliptical grain structures were observed at round locations, respectively. The grains at these regions were elongated or stretched as they underwent a large plastic deformation amount during the forming process. The typical optical microstructure of AA5052 and AA5083

### Table 1. (a) Forming conditions and specimens dimensions.

| Item | Material | Die temp. (°C) | Lubricant | Specimens status | Width DIM (mm) | Length DIM (mm) |
|------|----------|----------------|-----------|------------------|----------------|-----------------|
| 1    | AA5052-H32 | 410            | None      | Completed        | 75.46 75.43 75.45 | 152.02         |
| 2    | 410       | Used           | Completed |                  |                |                 |
| 3    | 450       | None           | Fail      |                  | 74.95 74.70 74.77 | 152.00         |
| 4    | 450       | Used           | Completed |                  | 75.41 75.44 75.40 | 152.00         |
| 5    | AA5083-O  | 410            | None      | Completed        | 75.37 75.36 75.38 | 151.98         |
| 6    | 410       | Used           | Fail      |                  | 75.45 75.44 75.46 | 152.00         |
| 7    | 450       | None           | Completed |                  | 75.40 75.39 75.40 | 151.94         |
| 8    | 450       | Used           | Completed |                  | 75.40 75.38 75.39 | 151.93         |

### (b) Forming conditions and specimens dimensions.

| Item | Clamping force (Tons) | Specimens status | Width DIM (mm) | Length DIM (mm) |
|------|-----------------------|------------------|----------------|-----------------|
| 1    | 20                    | Completed        | 75.36 75.34 75.35 | 151.98         |
| 2    | 15                    | Completed        | 75.37 75.35 75.38 | 151.98         |
| 3    | 10                    | Fail             | 75.16 75.98 75.12 | 152.01         |
| 4    | 5                     | Fail             | N/A N/A N/A      | N/A            |

### (c) Forming conditions and specimens dimensions.

| Item | Die Temp. (°C) | Specimens status | Width DIM (mm) | Length DIM (mm) |
|------|----------------|------------------|----------------|-----------------|
| 1    | 400            | Completed        | 75.27 75.23 75.28 | 151.75         |
| 2    | 410            | Completed        | 75.46 75.43 75.45 | 152.02         |
| 3    | 420            | Completed        | 75.38 75.38 75.36 | 151.94         |
| 4    | 430            | Completed        | 75.36 75.34 75.35 | 151.96         |
| 5    | 450            | Completed        | 74.95 74.70 74.77 | 152.00         |

### (d) Forming conditions and specimens dimensions.

| Item | Preheating time (s) | Specimens status | Width DIM (mm) | Length DIM (mm) |
|------|---------------------|------------------|----------------|-----------------|
| 1    | 60                  | Completed        | 75.46 75.43 75.45 | 152.02         |
| 2    | 120                 | Completed        | 75.41 75.44 75.40 | 152.00         |
| 3    | 180                 | Completed        | 75.39 75.35 75.39 | 151.98         |

### (e) Forming conditions and specimens dimensions.

| Item | Forming time (s) | Gas pressure (MPa) | Specimens status | Width DIM (mm) | Length DIM (mm) |
|------|------------------|--------------------|------------------|----------------|-----------------|
| 1    | 50               | 4                  | Completed        | 75.37 75.35 75.38 | 151.98         |
| 2    | 50               | 4                  | Completed        | 75.38 75.35 75.38 | 151.97         |
| 3    | 50               | 5                  | Completed        | 75.39 75.35 75.38 | 152.00         |
| 4    | 60               | 4                  | Completed        | 75.46 75.43 75.54 | 152.02         |
| 5    | 70               | 3                  | Completed        | 75.33 75.27 75.37 | 151.93         |
| 6    | 80               | 4                  | Completed        | 75.41 75.36 75.38 | 152.03         |
in the as-delivered condition as shown in Figure 10. The grains were fairly equiaxed. The grain size was measured by the linear intercept method. It is about 111.3 μm and 25.3 μm in average size, respectively, for AA5052 and AA5083.

**Dimensional tolerance analysis**

The specimens made of three type of die and two materials were divided into five groups to analyze the dimensional tolerance levels of rapid molding. Tables 2 and 3 shown the results of this analysis. Design dimension is the target value of the original design; measured mean dimension is the actual measurement average; linear dimensional error is the error from the target value; measured range is the difference between the maximum and minimum values in the group; and 6 × Standard deviation is each six times standard deviation of the group, and IT grade is international tolerance grade.

The two aluminum alloy sheet were continuously blown by using a demolding mechanism die and the mold temperature was controlled. Table 2 shows the measurement results for the 20 specimens examined. Comparison of the boards blown by the two materials, indicates a significant difference in the value of the wide side (B), while the long side (D), did not obviously differ between the materials, and was better than the wide side for both. The reason is the appearance design. A higher temperature is less susceptible to material shrinkage. In addition, the AA5083 had more concentrated dimensions and better IT grade than AA5052. These measurement results indicate that the material of the sheet affects the stability of the formed dimension.

An AA5052 sheet was used to blow continuously on three types of die and control process parameters stably. Measurement and statistics were taken for 30 pieces of each completed specimens, with results shown in Table 3. Regardless of the interaction of the mold, material, and input parameters, the IT tolerance accuracy level of the product was 10–14, which is similar to the tolerance level of the product of stamping and cutting. The IT grade of the quick plastic forming product in this study was 12, which is equivalent to the IT tolerance precision grade of the cut product, and better than the IT tolerance grade of the stamped product. The shallow rounded rectangular pan with formed products with poor IT tolerance grade, mainly because the removal method was to remove the specimens before and after the mold. Separating the mold produced jitter in different directions from the mold opening. Additionally, the poor IT grade on the long side was caused by largest shape being located on the parting line of the middle and lower molds. Therefore, the middle die may deform after a long period of use. As shows in the Figure 11, a trace is clearly visible. This trace mark the contact position between the middle die and the lower die, and is most likely to occur if the contact position is not flat enough affecting the tolerance.

![Figure 8. Tensile properties of AA5052 and AA5083.](image)

![Figure 9. Different locations along the transverse direction for specimens of the vertical wall of the rectangular pan die.](image)
Evaluation process efficiency

Table 4 shown the results from process efficiency analysis. Comparing the production time and manufacturing process of the three sets of die, die c had the best process efficiency because the demolding mechanism can significantly reduce the manual operation time and simplify the test piece production steps. In addition, all three sets had the same sheet preheating (step 1) and forming times (step 2), because the these are mainly affected by the material and mold shape, which is not the focus of this study, so set the same time. The process time influenced by the demolding mechanism begins from the movement of the machine to the

![Figure 10. Optical micrographs of the studied alloys observed in the sheet planes: (a) AA5083 (grain size ~20 μm) and (b) AA5052 (grain size ~80 μm).](image)

### Table 2. Tolerance analysis of two materials of specimens according to IT grade.

| Die/production | C/vertical wall rectangular pan | AA5052-H32 | Width | Length | AA5083-O | Width | Length |
|----------------|--------------------------------|------------|-------|--------|----------|-------|--------|
| Material       |                                |            |       |        |          |       |        |
| Input permanents| Width                         | Length     |       |        | Width    | Length |
| Design dimension| 75.40                         | 75.40      | 75.40 | 152.0  | 75.40    | 75.40  | 75.40  |
| Measured mean dimension| 75.42                         | 75.39      | 75.42 | 152.0  | 75.37    | 75.32  | 75.37  |
| Linear dimensional error| 0.023                         | 0.008      | 0.020 | 0.003  | 0.033    | 0.081  | 0.031  |
| Range of measurement| 0.150                         | 0.150      | 0.120 | 0.070  | 0.060    | 0.110  | 0.080  |
| 6× standard deviation| 0.260                         | 0.263      | 0.197 | 0.139  | 0.110    | 0.198  | 0.143  |
| Calculated IT grade| 11.59                         | 11.62      | 10.99 | 9.68   | 9.73     | 11.01  | 10.30  |

### Table 3. Tolerance analysis of three type of specimens according to IT grade.

| Input permanents | Rectangular open box | Width | Length | Shallow rounded rectangular pan | Width | Length | Vertical wall rectangular pan | Width | Length |
|------------------|----------------------|-------|--------|---------------------------------|-------|--------|---------------------------------|-------|--------|
| Design dimension|                      | 40.00 | 40.00  | 40.00                           | 118.35|        | 75.40                           | 75.40 | 75.40  |
| Measured mean dimension|                  | 40.00 | 40.01  | 40.02                           | 118.35|        | 75.40                           | 75.36 | 75.4   |
| Linear dimensional error|                  | 0.005 | 0.007  | 0.016                           | 0.001 |        | 0.001                           | 0.04  | 0.002  |
| Range of measurement|                   | 0.050 | 0.050  | 0.040                           | 0.080 |        | 0.21                           | 0.32  | 0.37   |
| 6× Standard deviation|               | 0.060 | 0.074  | 0.075                           | 0.098 |        | 0.37                           | 0.53  | 0.50   |
| Calculated IT grade|                   | 8.92  | 9.35   | 9.38                           | 9.13  |        | 12.35                          | 13.16 | 13.01  |

### Evaluation process efficiency

Table 4 shown the results from process efficiency analysis. Comparing the production time and manufacturing process of the three sets of die, die c had the best process efficiency because the demolding mechanism can significantly reduce the manual operation time and simplify the test piece production steps. In addition, all
operable range, and closes the temperature of the die when the door is closed. The ratio of each mold during this period was A:B:C = 80:180:10. Therefore, this design not only significantly reduces time costs but also reduces manpower. The table data clearly indicate that the maximum difference is the die temperature recovery time (die heating), because the equipment need to open the door when removing the specimens. Additionally, the temperature of the die falls due to the difference in internal and external temperature. Therefore, reducing the door opening time is the key factor to shortening the process time. The rectangular open box die and demolding mechanism die only have upper and lower die. The process time when using the demolding mechanism was less than half than without it.

### Conclusions

QPF (Quick Plastic Forming) is modified from SPF (Superplastic Forming) due to production cost effective consideration. Its justification as a feasible manufacturing method, especially for making smart phone cases, is further confirmed as its IT (international tolerance) grade is even superior to CNC machining combined with cost reduction. IT grade data of QPF is not available prior to this study. We have designed a novel fixture to run the dimensional tolerance measurement. Comparing with stamping manufacturing route, QPF can produce curled circumferential edges as its working principle is punchless, using pressure gas to blow metal sheet into a single mold. It is also suggested that 5083 is an potential aluminum alloy for QPF to make various kinds of complex shape and thin sheet products.

### Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.
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