Design of a fixture for single incremental forming (SPIF) process based on design for assembly (DFA) methods

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Abstract. This paper discusses the application of Design for Assembly (DFA) Method, Boothroyd Dewhurst to select the best design of a fixture for Single Point Incremental Forming (SPIF). The 3D design of fixtures was created using SOLIDWORKS 2016 software. This research will focus on the manual handling and insertion of the fixtures by reducing the number of parts and comparing between two designed fixtures. The chosen design has been made based on the best design efficiency. The result found that the application of DFA improved the design efficiency, where welded-based Design B is 35.62% greater than design efficiency of fastener-based fixture Design A which is 23.04%.

Keywords: SPIF; Fixture Design; Design for Assembly.

1. Introduction
Sheet metal forming is one of the most popular processes in manufacturing sector. Due to high flexibility in demands, industry nowadays more focus on producing low production quantities, design customization, low cost, complex geometries and the most importantly the quality of the finish part [1]. One of the processes that can meet all these criteria is incremental sheet forming (ISF). Frequently, the ISF process can be determined based on the size of the fixture and the geometry of the part. Typically, the fixture consists of top plate and base plate by clamped the sheet by series of threaded fasteners [2].

1.1. Single point incremental forming
Incremental sheet forming can be divided into single point incremental forming (SPIF) and two-point incremental forming (TPIF) [3]. One of the major advantages of SPIF is the process is die-less, more flexible and less tooling cost. Basically, in the SPIF, a forming tool movement controlled by a CNC machine or robot arm, push downward incrementally the clamped sheet metal and the process is continue until final profile obtained [4]. This process involves concentration force resulting from spinning of forming tool act on the sheet metal and friction forces occurred between the contacted surfaces produced the heat, thus, it facilitates forming of the required shape [5]. Figure 1 show the schematic diagram of the mechanism and basic parts involved in SPIF. Considering the understanding about SPIF process, the design of the fixture should have several criteria such as the blank space to downward force from rotating forming tools [6]. In addition, level of the fixture depends on the
maximum depth of SPIF process and capability of the frame structure of the fixture to mount at worktable due to process stability. All this aspect needs to be considered in the design of the fixture for SPIF process [7].

![Figure 1. Working principle of SPIF.](image)

1.2. Fixture design requirements
In manufacturing processes, applications of fixture are wide and therefore requires interchangeable and repeatable processes to produce same part but maintain the process position [8]. In ISF process, several parameters are crucial to control the magnitude of localized force applied to the sheet [9].

1.3. Purpose of fixture
Generally main purpose of fixture is to ensure the mounting of the workpiece is securable during the process and support to produce highly accuracy for the finished part [10]. Some basic purpose to develop the fixture is to quick, easy and consistently during locating the work piece. Besides, is to maintain the product quality consistently and guidance for cutting or forming process especially act as an assistant for unskilled operator and the most considerable using fixture is high interchangeability for mass production [11].

1.4. Elements of fixture
Basically, all fixtures consist of the following elements:
1.4.1. Locators: Locators is a fixed place on the fixture to insert the workpiece. It is used to ensure the position of workpiece to maintain during the process.
1.4.2. Clamps: Clamps is mechanism an applied force onto the workpiece either internal (mount at the fixture itself) or external (G clamp) clamp, to secure the workpiece is firmly fixed.
1.4.3. Fixture Body: Main frame or structure of the fixture. Fixture body try to maintain the relationship with the other fixtures elements such as locators, clamps and supporting parts.
1.4.4. Support device can be fixed or adjustable in order to improve some weaknesses of the fixture.

2. Methodology

2.1. Design for assembly (DFA)
Design for Manufacture and Assembly (DFMA) is a type of design approach that emphasizes on ease and efficiency of assembly process. By reducing the unnecessary part of a design, it possible to optimize the cost of manufacture and minimize an assemble time. DFMA terms is combination between Design for Manufacture (DFM) and Design for Assembly (DFA) [12]. DFA is a tool used to optimized the components in product design while DFM is a tool to optimize the manufacturing process in product design [13]. By referring DFA guidelines, it will assist the designer and manufacturer to understand the design rules that need to be follow when developing a product design.
According to Boothroyd Dewhurst method, the manual assembly process consists of two aspects. First is handling by means of orientating the parts and secondly is about the inserting by means of mating the parts to another group of parts [14]. The following experiment will be referred concept of alpha-beta orientation and applied digit codes from Manual Handling Classification and Manual Inserting Classification table [15]. Design efficiency can be calculated from the formula.

\[
\text{Design Efficiency} = \left(3s \frac{N_m}{T_m}\right) \times 100\% \quad (1)
\]

Where \(N_m\) is Theoretical Minimum Number and \(T_m\) is Total Part of the part to develop the fixture.

2.2. 3D design SOLIDWORKS
SOLIDWORKS 2016 has been used to design the 3D fixtures. The fixtures design emphasized on the basic technique to draw on 2D with specific dimensions, then convert to 3D by extrude features. Single part was designed in “Part” section. While combining of all parts to become one complete product will be carried out in “Assembly” section in SOLIDWORKS. The design of the both fixtures are based on the dimensions of the workpiece. Aluminium sheet type of AA6061-T6, AA5052-H32 and AA1100-H14 has been used with standard size 200mm x 170mm with 3mm thickness. Material structure for both design of fixtures used is aluminium profile 40mm x 40mm with same length for the Design Fixture A and different length for the Design Fixture B. Figure 2 and Figure 3 show the envelope dimensions for both fixtures.

![Figure 2. Dimension Design Fixture A.](image)

![Figure 3. Dimension Design Fixture B.](image)

3. Result and discussions
This section will focus on design analysis to determine the best design efficiency from both fixtures to achieve the objective of this research.
3.1. Design fixture A
This study will emphasis on of Design Fixture A. The design of the fixture creates by SOLIDWORKS 2016 software. Figure 4 show the Design Fixture A and Figure 5 show the exploded view of Design Fixture A.

![Figure 4](image1)
![Figure 5](image2)

Before determine the Theoretical Minimum Number (Nm), Design Fixture A need to disassemble to count the Total Part (Tm). Table 1 show the details part for Design Fixture A.

### Table 1. Total parts of Design Fixture A.

| Part no | Name            | Quantity | Material          | Function                          |
|---------|-----------------|----------|-------------------|-----------------------------------|
| 1       | Frame           | 12       | Aluminium Profile | Fixture main frame.               |
| 2       | Layer           | 1        | Mild Steel        | Base for the workpiece            |
| 3       | Cover           | 1        | Aluminium Plate   | Workpiece Locator                 |
| 4       | Toggle Clamp    | 6        | Stainless Steel   | Clamping the workpiece            |
| 5       | Tighten         | 4        | Aluminium Plate   | Tighten the workpiece             |
| 6       | Bracket         | 16       | Aluminium         | Connector between Frame structure |

3.1.1. Theoretical minimum number
Based on the Table 1, Total Parts for Design Fixture A are 40. To determine the Theoretical Minimum Number (Nm) of Design Fixture A, the parts list will be evaluating to obtain the Nm by mark 1 for essential part and 0 for non-essential part as shown in Table 2. Based on Table 2, total of Theoretical Minimum Number (Nm) of Design Fixture A are 36.

3.1.2. Operation time
Operation Time will be calculating based on the concept of $\alpha + \beta$ orientation and to estimate the handling and inserting time can be refer from Manual Handling Chart and Manual Inserting Chart. Table 3 shows data for the Assembly time for Design Fixture A.
Table 2. Theoretical Minimum Number (Nm) of Design Fixture A.

| Part no | Name             | Quantity | Theoretical Minimum Number, Nm |
|---------|------------------|----------|-------------------------------|
| 1       | Frame            | 12       | 1                             |
| 2       | Layer            | 1        | 1                             |
| 3       | Cover            | 1        | 1                             |
| 4       | Toggle Clamp     | 6        | 1                             |
| 5       | Tighten          | 4        | 0                             |
| 6       | Bracket          | 16       | 1                             |

Table 3. Assembly Time of Design Fixture A.

| Operation | Name        | No of items | α  | β  | α+β | Handling Code | Handling Time, s | Insertion Code | Insertion Time, s | Total Operating Time, s |
|-----------|-------------|-------------|----|----|-----|---------------|------------------|----------------|---------------------|------------------------|
| 1         | Beam        | 12          | 0  | 180| 180 | 1             | 5.27            | 5              | 9                   | 12                     | 174.84                 |
| 2         | Layer       | 1           | 0  | 180| 180 | 0             | 2.18            | 0              | 0                   | 1.5                    | 3.68                   |
| 3         | Cover       | 1           | 0  | 180| 180 | 0             | 2.18            | 0              | 0                   | 1.5                    | 3.68                   |
| 4         | Toggle Clamp| 6           | 180| 180| 360 | 1             | 3               | 3              | 8                   | 6                      | 54                     |
| 5         | Tighten     | 4           | 0  | 180| 180 | 0             | 1.88            | 3              | 8                   | 6                      | 31.52                  |
| 6         | Bracket     | 16          | 0  | 180| 180 | 1             | 2.06            | 4              | 9                   | 10.5                   | 200.96                 |

Total Operation Time 468.68

3.1.3. Design efficiency
Based on the Table 3, the total operation time is 468.68 second. Design Efficiency can be calculated by using equation (1)

Design Efficiency = \((3s N_m/T_m) \times 100\%\)
\(= ((3s \times 36)/468.68) \times 100\%\)
\(= 23.04\%\)

3.2. Design fixture B
The design of the Design Fixture B also created by SOLIDWORKS 2016 software. Figure 6 show the Design Fixture B and Figure 7 show the exploded view of Design Fixture B. Before determine the Theoretical Minimum Number (Nm), Design Fixture B need to disassemble to count the Total Part (Tm). Table 4 show the details part for Design Fixture B.

3.2.1. Theoretical minimum number
Based on the Table 4, Total Parts for Design Fixture B are 17. To determine the Theoretical Minimum Number (Nm) of Design Fixture B, the parts list will be evaluating to obtain the Nm by mark 1 for essential part and 0 for non-essential part as shown in Table 5. Based on Table 5, total of Theoretical Minimum Number (Nm) of Design Fixture A are 17.
3.2.2. Operation Time
Operation Time will be calculating based on the concept of $\alpha + \beta$ orientation and to estimate the handling and inserting time can be refer from Manual Handling Chart and Manual Inserting Chart. Table 6 shows data for the Assembly time for Design Fixture B.

![Figure 6. Design Fixture B.](image)

![Figure 7. Exploded view of Design Fixture B.](image)

| Part no | Name     | Quantity | Material      | Function                          |
|---------|----------|----------|---------------|-----------------------------------|
| 1       | Frame A  | 4        | Aluminium Profile | Fixture main frame.               |
| 2       | Frame B  | 4        | Mild Steel    | Base for the workpiece            |
| 3       | Frame C  | 4        | Aluminium Plate | Workpiece Locator                 |
| 4       | Base     | 1        | Stainless Steel | Clamping the workpiece            |
| 5       | G Clamp  | 4        | Aluminium     | Connector between Frame structure |

| Table 4. Total parts of Design Fixture B. |

| Part no | Name     | Quantity | Theoretical Minimum Number, Nm |
|---------|----------|----------|--------------------------------|
| 1       | Frame A  | 4        | 1                              |
| 2       | Frame B  | 4        | 1                              |
| 3       | Frame C  | 4        | 1                              |
| 4       | Base     | 1        | 1                              |
| 5       | G Clamp  | 4        | 1                              |

| Table 5. Theoretical Minimum Number (Nm) of Design Fixture B. |
## Table 6. Assembly Time of Design Fixture B.

| Operation | Name      | No of items | α   | β    | α+β | Handling Code | Handling Time, s | Insertion Code | Insertion Time, s | Total Operating Time, s |
|-----------|-----------|-------------|-----|------|-----|---------------|------------------|----------------|-------------------|------------------------|
| 1         | Frame A   | 4           | 0   | 180  | 180 | 0 7           | 2.65             | 3 8            | 6                | 34.6                   |
| 2         | Frame B   | 4           | 0   | 180  | 180 | 0 7           | 2.65             | 3 8            | 6                | 34.6                   |
| 3         | Frame C   | 4           | 0   | 180  | 180 | 0 7           | 2.65             | 3 8            | 6                | 34.6                   |
| 4         | Base      | 1           | 0   | 180  | 180 | 0 2           | 1.88             | 0 6            | 5.5               | 7.38                   |
| 5         | G clamp   | 4           | 180 | 180  | 360 | 1 8           | 3                | 9 2            | 5                | 32                     |

Total Operation Time 143.18

### 3.2.3. Design Efficiency

Based on the Table 6, the total operation time is 143.18 second. Design Efficiency can be calculated by using equation (1)

\[
\text{Design Efficiency} = \left( \frac{3 \times N_m}{T_m} \right) \times 100\% = \left( \frac{(3 \times 17)}{143.18} \right) \times 100\% = 35.62\%
\]

### 3.3. Comparison Data

#### Table 7. Comparison Data between Design Fixture A and Design Fixture B.

|                     | Design Fixture A | Design Fixture B |
|---------------------|------------------|------------------|
| Total Parts         | 40               | 17               |
| Total Operation Time| 468.68 s         | 143.18           |
| Design Efficiency   | 23.04%           | 35.62%           |

Table 7 show the significant improvement on Design Fixture B compare than Design Fixture A in terms of Total Parts, Total Operation Time and Design Efficiency.

### 4. Conclusions

Based on this research, the study about Design for Assembly (DFA) is very useful in order to achieve the best design by focusing in manual handling and inserting method. The design efficiency value is very significant in order to achieve the objective this research. Results show the relationship between the total operation time is inverse proportional with design efficiency. Which means, low total operation time will increase design efficiency. Selection codes on manual handling and inserting charts also may affect the result. Even the value of design efficiency is not very high, but by compared between two design of fixture, as a conclusion, Design Fixture B is better than Design Fixture A. For future work, this research will be continued by considering the practicality of the design. Furthermore, failure analysis of structure using Finite Elements Analysis (FEA) software during the SPIF process. This research can contribute some knowledge in the jig and fixture development field.

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