1. Introduction

Recently, the number of manufacturing processes for a product has increased because of the rapid advancement of manufacturing technology. Subsequently, manufacturing cost also increases as the number of the processes increases. One of the examples for manufacturing processes is a hole making process. Hole drilling takes up a large part of the manufacturing processes and also it is said that all the existing mechanical parts contain holes. There are several ways to make a hole. One of the representative methods is a drilling. Holes in mechanical parts have requirements such as hole diameter, tolerances, and surface finishes. To satisfy the requirement, several drills with different diameters and cutting tools, such as taps and reamers, are used to finish a single hole. In order to drill a large hole, a drill with a small diameter is applied to create a pilot hole. This is followed by the use of a larger drill to create desired hole sizes. In addition, based on the requirements, tap drill, which creates screw threads, reamer and boring bar, are used to finish a single hole. Therefore, to make holes, several tools are needed, which increases tool movement distance and number of tool switching. This results in longer manufacturing time and increase in manufacturing costs. Merchant indicated that 70% of manufacturing time consisted of tool movement and switching time (Merchant, 1985). Thus, optimizing the hole making processes can reduce the manufacturing time and increase the manufacturing efficiency. For industrial products, such as engine block, there are several holes with different hole diameter and tolerances are available. In order to make these holes, several tools are required to finish a single hole, which
makes the optimization of hole making complex. Previous studies on this topic focused on solving the hole-making problem by adopting approaches similar to the traveling salesman problem (TSP). For instance, Kolahan & Liang utilized tabu-search to minimize the total processing cost, which included tool travel time, tool switching time, and cutting time in hole-making operations (Kolahan and Liang, 2000). Ghaiebi & Solimanpur used ant-colony optimization algorithm to optimize a process in which several tools were required to finish a hole (Ghaiebi and Solimanpur, 2007). Their target involved minimizing tool airtime and tool switch time. Abu Qudeiri used genetic algorithm to optimize the operation sequence in a CNC machine with operations located in asymmetrical locations and at different levels (Abu Qudeiri et al., 2007). Their target for the research was to reduce the cutting tool travel path. Lim utilized a hybrid cuckoo search genetic algorithm to optimize the hole-making sequence (Lim et al., 2016). These studies considered machine tools to have movement control on 3-axis. Thus, it is difficult to apply the result of the research to the 5-axis machining, which consist of additional two rotational axis. The usage of the 5-axis machining is increasing since complex shapes can be machined in a single set-up, which gives greater machining productivity (Modern machine shop, 2004). In addition, in these studies, it is assumed that tool needed to make a hole are always available or only a single tool is needed to make a hole. However, in real working environment, number of the tools available are limited and also single tool cannot make a required hole diameter and tolerance in the most cases. Thus, the result of past researches is difficult to apply in real working environment. This research investigated hole-making optimization that can be applied to 5-axis machining with 3 linear axes (X, Y, and Z) and 2 rotational axes (A and C), considering the tool movement, tool switching, limitation in the tool, and the tolerances of the holes.

### 2. Hole-Making Optimization

With respect to industrial products, a hole requires several tools to drill to a specific size and tolerance of holes, especially, when holes with large diameters and strict tolerances are required. As the number of tools needed to make a hole increases, the tool movement paths become complex and unwanted tool movement, tool switch occurs. Because of that, manufacturing time increases. Thus, optimization of the hole-making sequence is needed.

#### 2.1 Hole-Making Optimization Method

Hole-making optimization can be done by brute-force approach and using the solving method for TSP. Brute-force approach calculates entire possible tool path pattern, and thereby calculates the optimized tool path pattern. However, this approach has a disadvantage, as calculations will take a longer time with increase in the number of holes. Thus, if a manufacturing model involves 11 holes with single operation, then 39.9 million patterns of possible tool path pattern occurs. To search optimized tool path pattern from the possible tool pattern, it will take about 8 hours to obtain optimized path pattern, using computer with Intel Core i7 – 4970. As the number of the hole increases, calculation time will increase in exponential growth. Thus, it will be impossible to calculate an optimal tool path in a reasonable time, as industrial products require the drilling of a large number of holes with several tools. Hence, certain algorithms are necessary for calculating the optimal path. Past studies applied the solving method for TSP. The TSP is a problem that is defined as minimizing the distance traveled by a salesman passing through N cities. Each city must be visited exactly once, and the salesman returns to the starting city at the end. The TSP is a NP-hard problem. Several algorithms including greedy algorithm, simulated annealing, genetic algorithm (GA), ant colony algorithm, and tabu-search algorithm were proposed to solve TSP. In this research, GA is used to solve the hole-making sequence optimization as hole making sequence optimization has a similar structure to TSP.

#### 2.2 Hole-Making Process Rule

Before applying GA to optimize a hole, the hole-making process must be set to each hole in the model. This is done to the model because optimization of the hole-making sequence is based on the hole-making sequence set to each hole. To determine the hole-making sequence, the hole-making process rules are shown in table 1. The rules are applied when all the needed tools are available. Each row lists the tolerance assigned to the holes while each column lists the diameters for each hole. The letter $d$ used in the table represents the target hole diameter. For example, if the target hole diameter is between 20 mm and 30 mm with a tolerance of H7, then for the hole-making sequence, the center drill is
applied at the beginning of the sequence. After the center drill, the tool with diameter $d \times 0.3$ mm is applied. The tool diameter is 0.3 times the hole diameter because the drill’s web thickness must be smaller than the pilot hole (Krar and St. Amand, 1983). The web thickness of the drill depends on the drill’s material. After creating a pilot hole, the tool with $(d - 0.2)$ mm is applied to create a pilot hole for the reamer. If the reamer does not have enough machining allowance, it will wear out and the machining diameter will decrease. After creating the pilot hole for the reamer, reamer is applied to the hole to obtain the desired finishing. In addition to the hole-making process in table 1, depending on the depth of the hole, the drills used to make a hole will also vary because the hole depth that a drill can create is different for each drill.

When tool usage is restricted, an end mill can be applied to create a hole. The end mill can create a hole using helical interpolation. The maximum diameter of the hole that an end mill can create is 1.8 times the tool diameter; the minimum diameter is 1.2 times the tool diameter. If a hole made using the end mill exceeds the maximum limit, then an uncut portion will be left in the middle of the hole. If the machining hole diameter is less than the minimum diameter, then the end mill will interfere with the uncut portion at the center of the hole. The rules for choosing end mills are discussed below.

1. The hole diameter that can be created using an end mill must be between 1.2 and 1.8 times the tool diameter. The largest end mill that satisfies this rule will be chosen as a substitute tool.
2. A drill will be used to create a pilot hole for the end mill. The tool diameter for the drill will be equal to or larger than the tool diameter of the end mill. The tool diameter for the drill chosen will be as large as possible. If a hole larger than the end mill is available before using the end mill, then drill will not be used.

For example, if there is a hole with a diameter of 26 mm and tolerance of H9, then the number of tools needed to create a hole is calculated as two. The flow of the tool selection process is outlined below, when all the needed tools are available.

1. From table 1, to create a pilot hole, a drill with tool diameter $d \times 0.3$ mm is needed. From the target hole size, a drill with tool diameter of 7.8 mm is chosen as the pilot hole drill.
2. After pilot hole is created, target hole size is drilled using a 26 mm drill.

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Hole Diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d \leq 20$</td>
<td>$20 &lt; d \leq 30$</td>
</tr>
<tr>
<td>H9</td>
<td>$d \times 0.3$ mm Drill</td>
</tr>
<tr>
<td></td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>$d$ mm Drill</td>
</tr>
<tr>
<td>H8</td>
<td>$d \times 0.3$ mm Drill</td>
</tr>
<tr>
<td></td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>$d$ mm Drill</td>
</tr>
<tr>
<td>H7</td>
<td>Center Drill</td>
</tr>
<tr>
<td></td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>$(d - 0.2)$ mm Drill</td>
</tr>
<tr>
<td></td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>$d$ mm Reamer</td>
</tr>
</tbody>
</table>
In this case, tool diameter needed for drilling the pilot hole was available. There are cases when the drill that matches the value of $d \times 0.3$ mm is not available. In such situations, the diameter for pilot drill will be rounded up. If there is a drill that matches the rounded up number, then that drill will be chosen for the pilot hole. If there is no drill that matches this number, then an end mill is selected as a substitute tool. Next, the process for choosing the end mill as a substitute tool is shown. The hole used to begin the hole-making sequence is same as the previous one. This time, however, the 26 mm drill is missing from the tool list. The tool diameters for drills are limited to under 20 mm and the available end mills are 10 mm, 15 mm, and 20 mm.

1. First, apply the basic drilling sequence from table 1. In the generated drilling sequence, the 26 mm drill is missing; an end mill will substitute for the 26 mm drill.
2. Next, the end mill that will substitute for the 26 mm drill will be chosen. From the available end mills, helical interpolation is applied to create a hole. The end mill diameters that satisfied the requirements were 15 mm and 20 mm. Since multiple end mills satisfied the requirement, based on the rule that the largest end mill is chosen, the 20 mm end mill will serve as the substitute tool.
3. After choosing the end mill, the drill that will create the pilot hole is chosen. The drill chosen must have a tool diameter that is the same or larger than the end mill diameter. Since the 20 mm drill is the only drill that satisfies this requirement, the 20 mm drill is chosen for the pilot hole.
4. When there are restrictions on tool availability, to make a 26 mm hole, a 7.8 mm drill is first applied. Then, a 20 mm drill is applied for the end mill's pilot hole. Finally, a 20 mm end mill is applied to create a 26 mm diameter hole using helical interpolation.

Based on these rules, hole-making sequence is chosen.

### 2.3 Hole-Making Optimization using GA

GA is applied to optimize hole-making processes. GA was proposed by Holland (Holland, 1992). GA is an optimization method that resembles the natural genetic evaluation process. GA begins by creating an initial population, which is generated randomly. Inside the initial population, solutions called chromosomes exist. After generating initial population, each chromosomes in the population are evaluated to measure its fitness. Based on the measured fitness, a few chromosomes from the current population are chosen as the parents. After choosing the parents, GA operations like crossover and mutation are applied to the parent chromosomes to produce new chromosomes called the offspring. Each offspring is evaluated after the offspring are created.

#### 2.3.1 Initial Population

Initial population is the population that is created at the beginning of the operation randomly. Initial population consists of the chromosome that shows the hole-making processes. Chromosomes contain genes, which emulates the hole. Inside the gene, there are hole information such as hole coordinates, hole diameter, tool used in that hole-making operation, and depth of the hole. Each chromosome’s fitness was evaluated after creating the initial population.

#### 2.3.2 Fitness Evaluation

Fitness evaluation is the step in which each chromosome is evaluated based on the evaluation function. In this research, manufacturing time, which includes tool moving time, tool switching time, and machining time, was used as an evaluation function. Additionally, rotation of the table was also considered in the manufacturing time calculation to imitate the movement of 5-axis machining.

For the tool movement calculation, Eq. (1) and Eq. (2) were used. Equations are based on the velocity distribution curve shown in Fig. 1. The pattern in Fig. 1 (a) involved cases in which the distance between the holes was sufficiently long for the tool to reach its rapid traverse rate. Figure 1 (b) involved cases in which the distance between the holes was insufficient for the tool to reach rapid traverse speed. In the equations, $T_m$ denotes the tool moving time, $P_l$ denotes the distance between the holes, $P_{v_a}$ denotes the distance needed to accelerate to rapid traverse, $V_{max}$ denotes the rapid traverse rate, $a$ denotes the acceleration rate to reach rapid traverse rate, and $T$ denotes the time to reach rapid traverse rate. Equation (1) was used when the tool did not reach rapid traverse speed because of the short distance between the
holes, and the Eq. (2) was used when tool reached its rapid traverse rate. $V_{\text{max}}$ and $a$ are using the values from the tool manufacture’s tool catalogue.

$$T_m = \frac{2P_l}{a} \quad P_l < P_{lc}$$  \hspace{1cm} (1)$$

$$T_m = (2 \times T) + \frac{P_l - P_{lc}}{V_{\text{max}}} \quad P_l \geq P_{lc}$$  \hspace{1cm} (2)

To calculate the distance between holes, Eq. (3), Eq. (4), and Eq. (5).

$$P_l = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$  \hspace{1cm} (3)$$

$$\begin{bmatrix}
x_3 \\
y_3 \\
z_3
\end{bmatrix} =
\begin{bmatrix}
\cos C & \sin C & 0 \\
-\sin C & \cos C & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos B & 0 & -\sin B \\
0 & 1 & 0 \\
\sin B & 0 & \cos B
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos A & \sin A \\
0 & -\sin A & \cos A
\end{bmatrix}
\begin{bmatrix}
x_2 \\
y_2 \\
z_2
\end{bmatrix}$$  \hspace{1cm} (4)$$

$$P_l = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2}$$  \hspace{1cm} (5)$$

$$T_R = \frac{\theta}{\theta_{\text{speed}}}$$  \hspace{1cm} (6)$$

Equation (3) is applied when the current and next hole exist in same surface. Additionally, $x_1, y_1, z_1$ denote the current hole position, $x_2, y_2, z_2$ denote the next hole position. Equation (4) and Eq. (5) are used when the current and next hole exist on different surfaces. Equation (4) represents the rotational matrix, and $x_3, y_3, z_3$ denotes the coordinates after the rotation. Furthermore, $C$ denotes the rotation angle on the Z-axis, $B$ denotes the rotational angle on the Y-axis, and $A$ denotes the rotational angle on the X-axis. The distance between the holes after the rotation could be calculated Eq. (5). Eq. (6) denotes the rotation time calculation. $T_R$ denotes the rotation time, $\theta$ denotes the rotation angle, and $\theta_{\text{speed}}$ denotes the rotation speed. Rotation angle is calculated based on the how much rotation is needed to move to next surface side assuming A and C axis can rotate. The rotation time was compared to Eq. (1) and Eq. (2). If the rotation time exceeded the time calculated in Eq. (1) and Eq. (2), then the rotation time was used as the moving time. With respect to tool switching, the position for tool switching was designated, and when the tool switching occurred, the distance between the tool switching point and the current and next holes was used as the distance to calculate the time.

In general, two equations are used to determine machining time. Equation (7) is used to calculate machining time.

$$\tau = \frac{P_l}{V_{\text{max}}}$$  \hspace{1cm} (7)$$

(a) Rapid traverse speed reached due to the long distance

(b) Rapid traverse speed not reached due to the short distance

Fig. 1 Velocity Distribution Curve
for drill, reamer, and boring bar.

\[ T_d = \frac{ld}{nf_r} \]  

(7)

\( T_d \) is the machining time, \( ld \) is the hole depth, \( n \) is the spindle speed, and \( f_r \) is the feed rate per revolution. The hole depth, spindle speed, and feed rate are set to each machining tool. The values used in the calculations were obtained from the tool manufacturer's catalogue. Equation (8) represents the machining time of helical interpolation using the end mill.

\[ T_E = \frac{\pi(D_h - D)}{f} \left( \frac{ld}{f_i} \right) \]  

(8)

In the Eq. (7), \( T_E \) is the machining time using helical interpolation, \( D_h \) is the target hole diameter, \( D \) is the tool diameter for the end mill, \( f \) is the feed rate, and \( f_i \) is the pitch rate, which shows how the end mill can go deep per revolution. This equation was given in the book by Isakov (2004). Using Eq. (1), Eq. (2), Eq. (7), and Eq. (8), the total machining time will be calculated for fitness.

### 2.3.3 Selection

Selection was performed after the fitness evaluation. Based on the fitness evaluation, a parent chromosome, which was used to create a new chromosome (called offspring) was chosen during selection. In this research, roulette wheel selection was used as the method for selection. Roulette wheel selection gives every chromosome a chance to become a parent chromosome. Thus, population will maintain its diversity. Equation (8) expresses the roulette wheel selection.

\[ P_i = \frac{f_i}{\sum_{k=1}^{N} f_k} \]  

(8)

In Eq. (8), \( P_i \) denotes the possibility of choosing chromosome \( i \), \( f_i \) denotes the chromosome \( i \)'s fitness. \( N \) denotes the number of chromosomes. Because of this, chromosome with higher fitness have higher chance to be chosen as a parent chromosome. Also, chromosome with lower fitness will have less chance to become a parent chromosome. Roulette wheel selection is named based on the image that roulette is turned and stopped at the pocket, which the size of the pocket is determined by the fitness value. Roulette wheel has a merit, but also it has a demerit. Because roulette wheel chooses the parent chromosome based on possibility, it may destroy the chromosome with best fitness at that point. To protect the best chromosome, elitist selection is also applied at the selection. Elitist selection preserves the best chromosome at that point and carries it to the next generation without any alteration.

### 2.3.4 Crossover

Crossover occurs after the parent chromosome are chosen in the selection step. Crossover occurs at a certain possibility, and there are several methods that could be used in the crossover. For example, in a single point crossover, a point is chosen, then a string from the beginning of the chromosome to the crossover point is copied from a parent, and the rest of the string is copied from the second parent. In contrast, two-point crossover involves choosing two crossover points. The string from the beginning of the chromosome to the first crossover point is copied from a parent, and then the string between first and second crossover points is copied from another parent. The string after the second crossover point is copied from the first parent. These are examples of typical crossover methods used in the GA. However, both of these crossover methods create chromosome that cannot be used as a solution. This is because some of the holes used in the crossover might be available as duplicated genes or missing genes. In this case, by comparing the original
parent chromosome and offspring chromosome, missing genes can be copied into the position of the duplicated genes to make the chromosome as a valid solution. However, in this method, the route that was obtained by crossover changes drastically that it will become same as a random search. Hence, in this research, partially-mapped crossover (PMX) was used. PMX was developed by Goldberg, and it is shown in Fig. 2. In Fig. 2, number inside the box represents the gene and the hole (Goldberg and Lingle, 1985). Following explains how PMX works.

1. First, two crossover points are chosen randomly. In the Fig. 2, dotted lines represent this crossover points.
2. After choosing the crossover points, genes between the crossover points are swapped. In the Fig. 2, 9 and 5, 10 and 1, and 8 and 4 are the pairs that are going to be swapped.
3. Next, offspring chromosomes are generated. At the beginning, offspring chromosome consists of same string as the parent chromosomes.
4. After generating offspring chromosomes, pairs that were determined in step 2 were swapped inside each offspring chromosome. Thus, in the Fig. 2, compared to parent chromosomes, position of the 9 and 5, 10 and 1, and 8 and 4 are swapped.

By using PMX, all the duplicated genes and missing genes are eliminated. After the crossover step, system enters the mutation step.

2.3.5 Mutation

In mutation step, mutation occurred in each offspring chromosome created in crossover step with a certain possibility. For this research, two points are randomly chosen and swapped when mutation occurred, as shown in Fig 3.

This method can prevent the genes to be missing from the offspring chromosome. The mutation was performed to
prevent answers from falling within a local optimum. After the mutation step, system moves to the termination step.

2.3.6 Termination

In the termination step, the algorithm checks whether it reached the target fitness or target generation numbers. If the target fitness number or generation number was reached, then the program stops at that point and shows the best solution at that point. If the target was not reached, then program returns to the fitness evaluation and the program continues to run until it reaches the target.

2.4 Hole-Making Optimization Validity Check

In this section, hole-making optimization system was compared to the brute force approach to verify its validity and usefulness. The model used in the comparison is shown Fig. 4. This model has eleven 15 mm diameter holes. In this comparison, it was assumed that required tolerance for each hole was H9 tolerance. In this situation, based on the hole-making process rule on table 1, to make a hole, 15 mm drill is required. Figure 5 shows the development view of the model with the optimized path obtained from both the brute-force approach and the GA. The blue line represents the path obtained by brute-force approach. Red line represents the path obtained by GA. The time taken to obtain the solution for brute-force approach was 31920 s or approximately 8.4 h, and machining time for brute-force approach was 8.54 s. The time taken to obtain the solution in the GA method was 361 s, and machining time was also 8.54 s. Calculation was based on the computer with intel core i7-4790. This result indicated that the GA could produce the same answer as the brute-force approach, which could produce the optimum solution. Additionally, the GA produced a solution in a much shorter time when compared to that of the brute-force approach, and this indicated the efficiency of the GA. Based on these results, validity of the system was confirmed.

3. Applying Hole-Making Process Optimization System
In this section, hole-making optimization system is applied to the engine block model shown in Fig. 6. The engine block dimensions were 500 mm (length), 400 mm (width), and 370 mm (height). The model consists of a 50 mm diameter hole, a 37 mm diameter hole, a 20 mm diameter hole, seventeen 12 mm diameter holes, nine 10 mm diameter holes, and ten 8 mm diameter holes. The holes were assigned to have certain tolerances as stated in table 2. In table 2, column states the diameter of the holes and row states the tolerances of the holes. In this model, the 50 mm, 37 mm, 20 mm diameter holes have H7 tolerance, 12 mm and 10 mm diameter holes have H9 tolerance. With respect to the 8 mm diameter holes, two holes have H9 tolerance and remaining eight holes have H8 tolerance. Table 3 lists the parameters used for the GA. Table 4 lists the parameters used for calculating tool moving time. Optimization system was applied in two situations. First situation is where all the needed tools for machining is available. Second situation is where available tools are restricted.

3.1 Hole-Making Process Optimization without Tool Usage Restriction

In this section, the hole-making process is optimized for the case when all the tools needed for making a hole are available. Table 5 shows the hole-making process based on the hole-making process rule shown in table 1. In the model, holes with diameters 20 mm and larger have H7 tolerance. Thus, to make a hole, the center drill is applied at the beginning of the sequence. After applying center drill, the \( d \times 0.3 \) mm drill is used to create a pilot hole.
### Table 5  Hole-Making Process without Restriction

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Hole Diameter [mm]</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>20</th>
<th>37</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H9</strong></td>
<td>8 mm Drill</td>
<td>10</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H8</strong></td>
<td>7.8 mm Drill ↓ 8 mm Reamer</td>
<td>Center Drill ↓ 19.8 mm Drill ↓ 20 mm Reamer</td>
<td>Center Drill ↓ 12 mm Drill ↓ 36.8 mm Drill ↓ 37 mm Boring Bar</td>
<td>Center Drill ↓ 15 mm Drill ↓ 49.8 mm Drill ↓ 50 mm Boring Bar</td>
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<td></td>
<td></td>
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<tr>
<td><strong>H7</strong></td>
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</tbody>
</table>

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### Table 6  Relationship between Tools and Line Colors

<table>
<thead>
<tr>
<th>Tool Change</th>
<th>36.8 mm Drill (L/D = 2)</th>
<th>6 mm Drill (L/D = 2)</th>
<th>37 mm Boring Bar</th>
<th>8 mm Reamer</th>
<th>20 mm Reamer</th>
<th>15 mm Drill (L/D = 2)</th>
<th>49.8 mm Drill (L/D = 2)</th>
<th>50 mm Boring Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mm Drill</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Center Drill</td>
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<td>7.8 mm Drill (L/D = 2)</td>
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<tr>
<td>7.8 mm Drill (L/D = 5)</td>
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<tr>
<td>8 mm Drill (L/D = 2)</td>
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<tr>
<td>10 mm Drill (L/D = 5)</td>
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<td>10 mm Drill (L/D = 3)</td>
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<tr>
<td>12 mm Drill (L/D = 5)</td>
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<tr>
<td>12 mm Drill (L/D = 2)</td>
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</table>
Table 7  Hole-Making Process with Restriction

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Hole Diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td>H9</td>
<td>8 mm Drill</td>
</tr>
<tr>
<td>H8</td>
<td>7 mm Drill ↓ 6 mm End Mill ↓ 8 mm Reamer</td>
</tr>
<tr>
<td>H7</td>
<td>Center Drill ↓ 15 mm Drill ↓ 15 mm End Mill ↓ 20 mm Reamer</td>
</tr>
</tbody>
</table>

After that, a drill with diameter \((d-0.2)\) mm is applied to create a pilot hole for the reamer or boring bar. After creating the pilot hole, the reamer is applied for the 20 mm diameter hole. For the 37 mm and 50 mm holes, the boring bar was applied to finish the holes. The 12 mm, 10 mm, and two 8 mm holes were required to have H9 tolerance. Thus, a drill with the target diameter was applied to make a hole. The remaining 8 mm holes have H8 tolerance. In this case, a drill with diameter \((d-0.2)\) mm was first applied to create a pilot hole for the reamer. Next, the reamer was applied to finish the holes. In Fig. 7, the hole-making process optimized by system is shown. Table 6 shows the relationship between the tools and line colors. From the calculations, the number of tools used was 55 and total machining time was 184.7 s. The total calculation time was 460 s.

3.2 Hole-Making Process Optimization with Tool Usage Restriction

In the previous section, the hole-making process optimization was conducted under ideal conditions, where all the tools needed were available. In this section, the tools that can be used in hole making are restricted. Tools that can be used are the reamer, boring bar, and drill with tool diameters 1–15 mm in 1 mm increments, 20 mm, 25 mm, and 30 mm. The end mills available are 5–10 mm, 15 mm, 20 mm, 25 mm, and 30 mm. In this situation, the pilot hole for the reamer and boring bar cannot be used. Thus, the end mill will be used as a substitute tool. The hole-making process is shown in table 7. For the 8 mm reamer pilot hole, the 6 mm end mill was used with the 7 mm drill. The 15 mm end mill was applied to make a 19.8 mm hole. For the pilot hole for the boring bar, the 30 mm end mill was applied for both 37 mm and 50 mm diameter holes. The optimized hole-making process is shown in Fig. 8. The relationship between tools and line colors are shown in table 8. From the system, the tools were used 66 times with 16 different tools. Total machining time was 224.7 s. Total calculation time in this situation was 742 s. The calculation time is longer due to the program to search for the replacement tools.

4. Conclusion

In this paper, hole-making optimization was performed using a GA. The hole-making optimization system proposed in the paper considered 5-axis machining, tool movement, tool switching, the limitation in the tool, and the tolerances of the holes. System was compared against the brute-force approach and obtained the same result in significantly shorter time. The system was also applied to the engine model in two situations, where tool usages are
restricted or not. For future work, system needs to consider the effect of the drill material and the work material. Since a few drills can make a hole with only a single operation, and this could reduce machining time and change the hole-making process. Also, another future work that needs to be considered is to shorten the computational time for future work. This can be done by optimizing the program by using efficient functions and reducing the number of the loops in the program. Since this program requires large number of loops for calculation, resulting computational time will be large that it may not be suitable for actual workshop.

References


