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Analysis of five- and six-machine micro-factory layouts for micro-pump productivity improvement †

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Abstract

In the present study, analyses of two micro-factory layouts were performed to improve its micro-pump production rate and efficiency. For the purpose of the analysis, the two layouts, Layout A (existing) with five micro machines (including one micro milling machine) and Layout B (proposed) with six micro machines (including two micro milling machines), were constructed in the virtual environment. First, Layout A was simulated to predict the production time and to calculate the production rate and efficiency. The robot-arm waiting time, which was considered as the bottleneck, had a significant effect on the production rate. Second, to alleviate this bottleneck, we introduced, based on the robot-arm reach envelope concept, another micro milling machine to the Layout A, and named this new scheme Layout B. In the results of our analysis, Layout B improved the production rate by about 1.88 times and enhanced the efficiency by a factor of 1.57.

Keywords: Micro factory; Micro pump; Production time, Production rate; Robot-arm waiting time

1. Introduction

A "micro factory," which is terminology proposed by the Mechanical Engineering Laboratory (MEL) of Japan in 1990, is a miniaturized production system designed specifically for the high-precision, high-throughput, but low-cost manufacture of micron-to-millimeter-sized parts and products. To date, many micro factories have been proposed by researchers [1-7]. The factory layout involves the selection and arrangement of machines, material handling devices and path, resulting in low cost and time involved in manufacturing a product. Many methods exist by which a layout can be both designed and analyzed. The earliest methods involved drawing plan views of different arrangements among which, after a thorough discussion involving all of the pertinent departments of the organization, the best one was selected. Another method entailed moving both 2D templates and 3D models on a grid until a satisfactory layout presented itself. These methods are imprecise in determining locations, inadequate for accurate time or cost analyses, and quite cumbersome and time-consuming overall. Conventional analytical systems are capable of providing statistical feasibility evaluation of targeted factory designs. With these systems, however, designers cannot get a feel for the actual setting of a factory design. With the advent of the CAD system, which allows the user to build templates, and models, move them around on the screen, perform an analysis within a few hours and easily accomplish re-layouts, the aforementioned problems were, to a certain extent, resolved [8-11].

In today's hyper-competitive environment, manufacturing organizations are continuously searching to develop and fund projects that will reduce manufacturing costs and increase productivity [12, 13]. Digital manufacturing, a software technology combined with manufacturing methods that has become a key component of PLM, has emerged to help manufactures meet those objectives. Digital Manufacturing offers the ability to virtually design, optimize, simulate and then execute, with a high degree of predictability, a manufacturing process. It closely couples the process design function with the product design function to transform production processes and business initiative. In defining and optimizing manufacturing processes, it manages manufacturing process information and supports effective collaboration among engineering disciplines. The goal of the digital manufacturing, in short, is to provide the manufacturing community with solutions to create, validate, monitor and control agile production processes [14, 15].

The micro factory specifically offers a considerable machining capability and flexibility. Given its miniature size, for

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example, it is possible to re-layout a micro factory according to changed production requirements. Indeed, showing how a micro factory can enable flexible factory, improve the efficiencies of micro mechanical fabrication [16] and enhance production throughput can greatly expand its applications. In the present study, using digital manufacturing, we constructed an existing micro-pump-producing micro factory in the virtual environment. We designed a new system to enhance the production rate and the overall efficiency of the existing system. For digital materialization of the new paradigm, the components of our micro factory were modeled using a 3D CAD system and simulated by means of UML (Unified Modeling Language) and object-oriented logical analysis. The UML is a non-proprietary general-purpose object-modeling language that includes a standardized graphical notation for creation of abstract models of systems. Object modeling, employing a standardized set of symbols, arranges those symbols to model (part of) an object-oriented software design or system design.

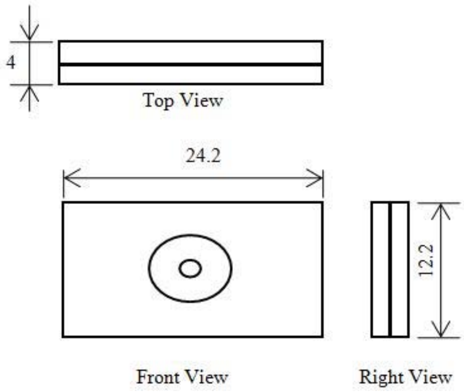
2. Related works

A micro factory is adequate for entire manufacturing processes, just like macro-factory. Nonetheless, a micro factory's potential utility in improving productivity and efficiency in micro product manufacturing has not been adequately considered. We used the digital manufacturing approach to construct our micro factory for two different micro-pump-manufacturing layouts, called Layout A and Layout B, preparatory to an analysis of their productivity and efficiency improvements. To date, many indexes have been proposed for calculation of micro factory efficiency in considering of system cost, production time, energy consumption and environmental impact. In 2006, AIST Japan proposed an index for calculation of the efficiency of a manufacturing process, based on its time duration and using the example of miniature ball bearing assembly [17]. In 2009, we proposed an index for calculation of the efficiency of a micro factory, based on the time required for each manufacturing process, the cost of the system and the energy required for production [18]. There are many strategies for improvement of the efficiency and productivity of systems, such as changing a system configuration or layout, modifying product design, and optimizing manufacturing processes. In the present study, we considered a change of system configuration, or layout, to enhance the efficiency and production rate of a micro factory. A micro factory was modeled in two layouts differing according to the number of micro milling machines. Analyses were performed considering the robot-arm waiting time. Both system layouts were simulated in the virtual environment to predict the production time and to calculate the production rate and efficiency.

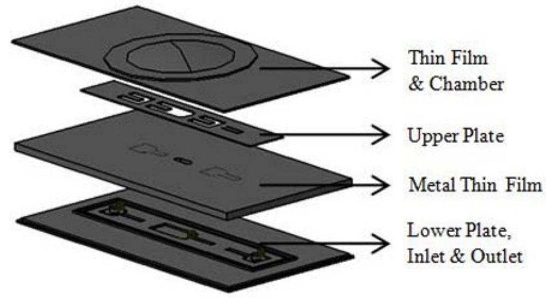
3. Analyses of micro-factory layouts

3.1 Micro pump

Our micro factory was designed to manufacture micro pumps. Fig. 1(a) indicates the size of the micro pump, and Fig. 1(b) is a 3D model derived with the 3D CAD system. The micro pump is 24.2 mm long, 12.2 mm wide, and 4 mm thick. It includes an upper plate, a chamber, a piezo electric thin film, a metal thin film, a lower plate and an inlet/outlet. The total material cost (M) of the micro pump according to the micro factory research centre, Korea, is about 300 won.



(a) Size of micro pump in millimeters



(b) Three-dimensional model of micro pump

Fig. 1. Micro pump.

3.2 Layout A with five micro machines

Our existing micro system with five micro machines, Layout A, includes a micro mill, a micro EDM machine, a micro press, a micro robot and an assembly machine. The costs of the micro machines are 25, 25, 30, 16 and 20 million won respectively. The total cost, then, is 116 million won. Shown in Fig. 2 is the 3D model of our micro-factory system, again in Layout A. Here we have two input terminals: one is for aluminum metal thin film, and the other is for the upper and lower plates of the micro pump. The process sequence, charted in Fig. 3, is as follows : At one end the aluminum metal thin film is inputted into the micro press preparatory to the pressing operation; after the pressing operation, the metal thin film is loaded into the EDM machine for the machining operation, and subsequently transferred to the assembly machine; at the other end, the upper plate is loaded into the micro milling machine for machining, after which it is transferred to the assembly machine; next, the lower plate is loaded into the micro milling machine and then transferred to the assembly

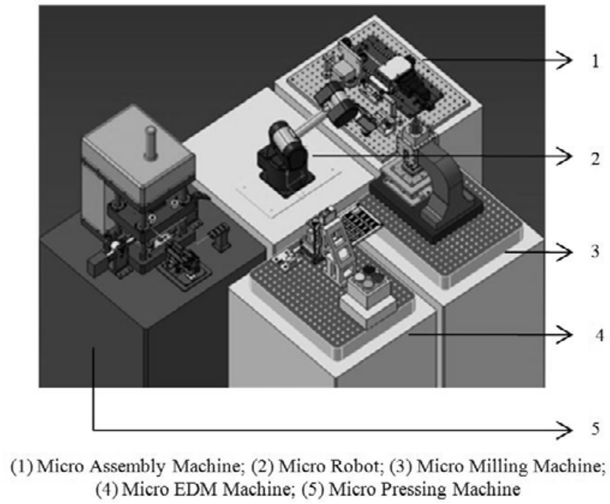


Fig. 2. Layout A of system with five micro machines (3D).

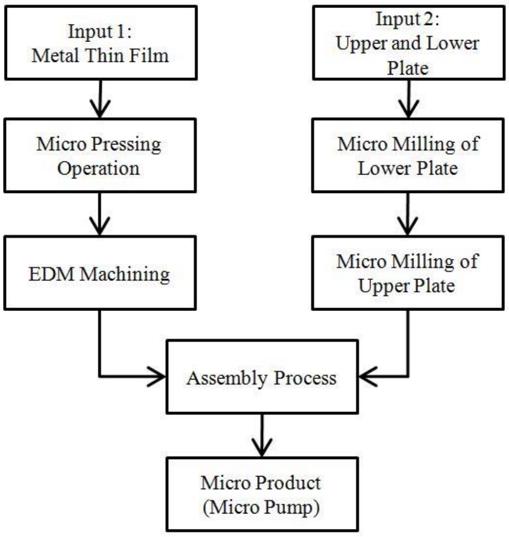


Fig. 3. Manufacturing process sequence in Layout A.

machine; in the assembly machine, finally, the upper plate, lower plate and metal thin film are assembled as a micro pump.

As we mentioned earlier, conventional analytical systems are capable of providing statistical feasibility evaluation of a targeted factory design; however, designers cannot get the feel for the actual setting of such a design. With the advent of the CAD system these problems were solved, at least to an extent. In the present study, our micro factory was simulated in the digital environment as per the process sequence defined. From the simulation, the time required to perform each operation, for example run time, was measured, and the results are tabulated in Table 1. From these results, we calculated that the total run time required to produce a micro pump is about 1255.7 seconds. On this basis, our factory, running continuously, would produce 69 units per day.

The robot arm has been utilized to transfer materials between micro machines. As per the process sequence then, the robot arm has to wait while a processes completes. In the manufacturing process for Layout A, the robot arm has to wait during the pressing operation, lower-plate machining, EDM machining, and upper-plate machining. Table 2 shows inter process categories of robot-arm waiting time, the time required for each category in seconds. These waiting times have a significant impact on both the total run time required to produce a micro pump and the overall production rate, and we considered them to constitute a system bottleneck. Most notably in this regard, the lower and upper plates are manufactured by the micro milling machine consecutively, obliging the robot-arm to wait for 580.8 and 311.4 seconds, respectively. We could say therefore that the milling operation is the major cause of the bottleneck problem.

Table 1. Time required for each process per unit in Layout A.

Micro Machines	Run Time	Number of Machines
Mill	10 min	1
Press	31 sec	1
EDM	5 min	1
Assembly	5 min	1
Robot	24.7 sec	1

Table 2. Robot-arm waiting time in Layout A.

Categories of robot-arm waiting time	Time (sec)
Pressing process	6.3
Lower-plate manufacturing	580.8
EDM machining	280.2
Upper-plate manufacturing	311.4

3.3 Layout B with six micro machines

As we explained, there are many strategies for improving system efficiency and productivity, such as changing the system configuration or layout, modifying the product design, and optimizing the manufacturing process. We considered changes to our system configuration, or layout, in order to enhance the efficiency and production rate of the micro factory. To alleviate the bottleneck issue in Layout A, we here propose a new layout called Layout B, which adds, according to the concept of the robot-arm reach envelope, a second micro milling machine to Layout A (as shown in Fig. 4) and the corresponding process sequence (Fig. 5). A Layout B simulation was then performed to measure the robot-arm waiting times, which are tabulated in Table 3.

With Layout B, the upper and lower plates were machined from the micro milling machine simultaneously rather than consecutively. In fact, we could see the difference in the robot-arm waiting time between the two layouts (see the Table 4 comparison). The robot-arm waiting time for upper-plate machining was reduced from 311.4 to 20.8 seconds, which repre-

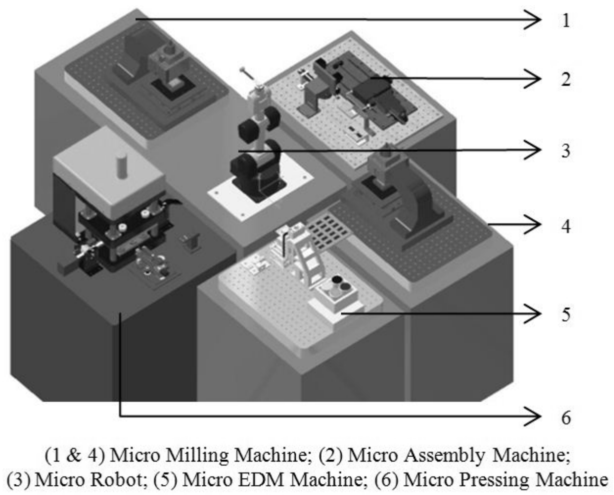


Fig. 4. Layout B with six micro machines (3D).

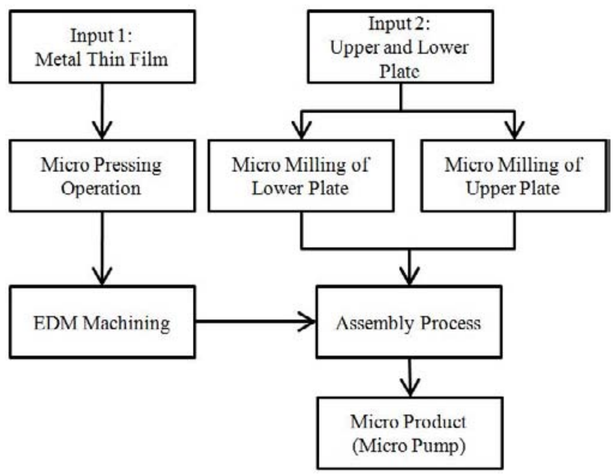


Fig. 5. Manufacturing process sequence in Layout B.

sents a savings of about 290.6 seconds. Next, the robot- arm waiting time for lower-plate machining was reduced from 580.8 to 270.8 seconds, for a savings of about 310 seconds. The waiting time for EDM machining was increased by 9.7 seconds. The total run time to produce a micro pump with Layout B, as measured in the simulation, was about 664.8 seconds. This means that we would produce about 130 units per day by running our micro factory continuously. Therefore, an almost 1.88-times increase in production rate was achieved by adding another milling machine to the existing Layout A (i.e. with Layout B).

From the micro-factory efficiency perspective, the efficiency of the layouts was calculated, based on the index proposed [18]. This index was calculated with the input and output parameters of the system. The input parameters include the cost of the system, the processing time and the energy required. The output parameter is the number of products manufactured by the micro factory. As calculated, the total cost of the micro system is 116 million won, and in addition, the operating cost

Table 3. Robot-arm waiting time in Layout B

Categories of robot-arm waiting time	Time (sec)
Pressing process	6.3
Lower-plate manufacturing	270.8
EDM machining	289.9
Upper-plate manufacturing	20.8

Table 4. Waiting time comparison of Layout A and B.

Categories of robot-arm waiting time	Time (sec)		
	Layout A	Layout B	Time Difference
Pressing process	6.3	6.3	0
Lower-plate manufacturing	580.8	270.8	310
EDM machining	280.2	289.9	9.7
Upper-plate manufacturing	311.4	20.8	290.6

was assumed to be 2 million won. The manufacturing space available was 500 x 600 x 860 centimeters, and the value of the space was assumed to be 8 million won. The total cost of the system, then, is 126 million won for Layout A and 151 million won for Layout B. The total energy required for the processes was calculated by multiplying the power of the motor and the total time required. Based on the efficiency index proposed [18] and the above-mentioned data, the efficiency indexes for Layout A and Layout B are 0.0095 and 0.015, respectively. Thus, we could say that Layout B, which adds a second milling machine to the existing layout (i.e. Layout A), is 1.57 times more efficient than Layout A.

4. Conclusions

We introduced and explained our micro-factory configuration and its micro-pump-manufacturing process. The micro factory was simulated in the virtual environment to determine the production time and identify any bottleneck problems. Its compactness, and flexibility allows for easy and effective system re-layouts; indeed, not only product design but also production processes and systems can be changed concurrently to maximize system efficiency and production rates. Moreover, it is easy to implement the concurrent design strategy in the virtual environment. All in all, the micro factory presents the possibility of a future manufacturing systems for micro mechanical fabrication of diverse products. In our simulations, we found that the robot-arm waiting time incurs a bottleneck problem, negatively affecting the production rate and efficiency. To minimize this bottleneck problem and maximize the production rate and efficiency, a proposed new micro factory layout, one that adds a second micro milling machine to the existing layout, was simulated. According to the results, we can report that the new layout improves the production rate and enhances the efficiency by factors of about 1.88 and 1.57, respectively.

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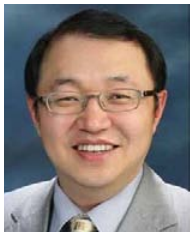

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