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Investigation of Sustainable and Reliable Manufacturing System Based on the Environmental Impact

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Abstract:

Recently, eco-friendly machining has been drawing attention in manufacturing field. Especially, environmentally conscious cutting process has been developing widely. However, there is few method that achieves low environmental impact in final polishing field. Here, a new polishing method with fixed-abrasives was proposed, and compared with conventional method from a viewpoint of environmental impact. Environmental impact assessment by LCA and energy consumption was compared in manufacturing phase and disposal phase. As a result, it was found that polishing by human work was an eco-friendly process, even if it was compared with desktop size machine manufacturing. Moreover, the effectiveness by using fixed-abrasive process has been clarified in disposal phase.

Keywords: Sustainability, Reliability, Manufacturing System, Environmental Impact, LCA

1. Introduction

A word “environment” is coming to be added with performance of conventional product and manufacturing cost in 21st century. In fact, many kinds of improvement has been tried in the manufacturing field to achieve minimum CO₂ emission, which is a requirement of ISO14001.

In this study, polishing process, which is a necessary final finishing in manufacturing field, has been drawing attention. Eco-friendly approach is also conducted in polishing process. Polishing mainly consists of two process, fixed-abrasive process and loose-abrasive process. Moreover, loose-abrasive process can be mainly separated to lapping and polishing. Lapping mainly makes a role for obtaining a flat surface. More precise process to obtain finer surface topography is called as polishing. A surface will be polished until the surface roughness P-V will achieve to nano-order^{[1-4],[11],[16]}.

In final polishing field, fixed-abrasive process is required alternative to loose-abrasive process, due to the disposal issue caused by large amount of slurry. There is also a demand from operators to reduce the lubricant to improve their working environment. In the case of loose-abrasive process, a mix of abrasive grains, chips, water and oil, is generated. Conventionally, reclamation disposal is conducted as industrial waste for these mixtures. However, it is difficult to have a place for reclamation disposal now^{[3],[8]}.

On the other hand, conservation of energy is also required in manufacturing field. It is thought that energy consumption will be increase if a large size machine is used. In this study, an idea “a small part should be processed with a small machine” was proposed. Downsize of machine will be effective to reduce the

manufacturing energy. Following this idea, polishing with small-sized machine was attempted in this study. Moreover, above-mentioned fixed-abrasive process also has advantage in saving energy. This is because that, power consumption related to cutting fluid has 30-40% in total power consumption of tool machine^{[3],[5-7]}.

In this report, polishing process was tried to evaluate from a viewpoint of environment impact. Two manufacturing process were mainly picked up. One is a polishing process with fixed-abrasive and small-sized machine. Another is a conventional polishing process with human work. Effectiveness of using fixed-abrasive, and downsizing of tool machine was being attempted from the environmental viewpoint. Moreover, these were evaluated separately, in manufacturing phase and in disposal phase.

2. Conventional polishing method

Polishing process with human work is picked up as a conventional final finishing process. Here, human, polisher, and slurry are taken into account. Figure 1 shows the conventional polishing method.

Fig. 1 Conventional polishing method

2.1. Human work model

This polishing is conducted by human work. Human work will be equivalent object with manufacturing, so that emission from human or energy consumption of human is considered^[1].

The following idea was considered regarding to CO₂ emission from human. Food, which human eats, is grown up by absorbing CO₂ in the air. Thus, it is generally said that CO₂ emission from human will not increase CO₂ of the earth. This is carbon-neutral. The problem is that CO₂ emission coming from burned fuel. This CO₂ includes fuel for driving a farm tractor, and energy consumption for production of fertilizer and agricultural chemicals. In a word, CO₂ comes from fossil fuel which is necessary to convert CO₂ to organism as a food. In this study, the target is polishing process, and only in manufacturing phase and disposal phase. Thus, human work can be taken into account as equivalent to manufacturing energy.

Here, human breath while working is considered. Amount of human breath is 8.6 m³ in one day. Moreover, amount of CO₂ in human breath is assumed to be 4%. Thus, CO₂ emission in one day is calculated to be 0.34 m³. The specific gravity of CO₂, compared to the air, is 1.53. This weight will be 0.6 kg. Polishing process time is assumed to be 30 min for one process. Thus, CO₂ emission from human while polishing process is about 0.0125kg.

Next, energy consumption while human work is represented by average. The work is assumed to be equivalent to daily hand washing process. The human is assumed to be male, 30 years old, and the weight is 70kg. The process time is 30 min. As a result, energy consumption is calculated to be 0.136 kWh^[2].

2.2. Polisher

Polishing pad after used should be abandoned following disposal rules, and it was regarded as industrial waste. Polishing pad has potential to generate harmful gas, which is bad for environment. The pad material is assumed to be polyurethane, one piece (60g) is used for one process, and is going to be waste. Some recycle methods are proposed for polyurethane, but it has not been general yet. One of the reasons is its cost. It is effective to use for fuel as thermal recycle. However, there is a problem of occurrence of large amount of NO_x. The target of impact assessment on polisher is disposal phase. Disposal method is assumed to be incineration, and the following products will be generated; CO: 173, CO₂: 343, methane:21, ethylene: 57, benzene: 49, styrene: 45, chloride HCl: 0.5, SO_x: 0.1, NO_x: 0.8, nitric acid HNO₃: 0.6, cyanogens HCN: 126, ammonia NH₃: 9.0. The unit is mg/g.

2.3 Slurry

The removal rate is assumed to be about 30 nm/min,

and the process time is 30 min. Slurry flow is assumed to be 100 ml/min. Polisher will be industrial waste, and reclamation disposal will be conducted^[9-10],12-16].

3. Proposal of polishing method with fixed-abrasives

We propose a new fixed-abrasive polishing process. This method uses a small-sized machine, and a grindstone is applied to the workpiece with low pressure. Reduction on environmental impact will be expected by downsize of machine and using fixed-abrasives. Here, a small-sized machine, grindstone, and lubricant were taken into account.

3.1 Small-sized machine

The idea is "a small part should be processed with a small machine." In this study, a desktop size robot (Mitsubishi, RP-3AH) was used as a small machine, as shown in Fig. 2. A polishing tool, as shown in Fig. 3, was installed on the machine. Grindstone is attached on the bottom. This unit makes it possible to apply low and constant pressure to the processing part by changing the force. Energy consumption while process was 700 kWh. Process time was 30 min.

Fig. 2 Robot for polishing

Fig. 3 Polishing tool

3.2 Lubricant

Water was used as lubricant. The amount is assumed to be the same as slurry flow in section 2.3. Sewage disposal was selected for this disposal.

3.3 Grindstone

Grindstone was used to achieve a fixed-abrasive process. Dropout and wear of grindstone are assumed not to occur. In the proposed method, the removal rate was $0.01 \text{ mm}^3/\text{min}$, and the process time was 30 min.

3.4. Potential of proposed method

In this section, finishing examples by using proposed method are shown.

Figure 4 shows the processing part, and the grindstone moves as indicated in Fig. 4. A diamond stone was used in the experiment. The workpiece was a borosilicate glass, and its surface was the target of finishing. Tables 1 and 2 tabulate the specifications of the grindstone and the workpiece. Water was used as lubricant. Pre-finishing was performed prior to finishing to keep the initial condition of the grindstone and the workpiece the same. Tables 3 and 4 list the pre-finishing and finishing conditions.

Fig. 4 Processing part

Table 1 Specification of grindstone

Abrasive grain	Diamond
Grain size	#8000
Mean grain diameter d_g (μm)	1
Bonding material	Vitrified
Volumetric grain percentage V_g	0.28
Concentration	100
Stone size (mm)	$3 \times 3 \times 4$

Table 2 Specification of workpiece

Material	Borosilicate glass
Main component	SiO_2
Size (mm^3)	$26 \times 76 \times 1$
Hardness	630HV
Roughness (nmRa)	2

Table 3 Pre-finishing conditions

Before finishing with	#8000
Grain size	#8000
Stone pressure P_n (MPa)	0.5
Maximum crossing angle Θ_{max} (deg.)	30
Cutting speed V (m/min)	2.5
Oscillation amplitude (mm)	0.5
Super-finishing area (mm)	5×5
Cutting distance (m)	5
Surface roughness (nmRa)	15

Table 4 Finishing conditions

Grain size	#8000
Mean grain diameter d_g (μm)	1
Stone pressure P_n (MPa)	0.1-0.5
Volumetric grain percentage V_g	0.28
Maximum crossing angle Θ_{max} (deg.)	10
Cutting speed V (m/min)	2.5 (m/min)
Oscillation amplitude (mm)	0.5 (mm)
Super-finishing area (mm)	5×5 (mm)
Cutting distance (m)	1-100 (m)

Figure 5 shows the variation of the surface finish with stone pressure P_n . Figure 6 shows SPM scans of the finished surface. The surface finish decreased with decreasing stone pressure, as shown in Fig. 5. Moreover, using fine abrasive grains, such as #8000, ductile cutting was achieved, and crack formation can be prevented, as shown in Fig. 6. The pressure used during super-finishing is typically about 1-3 MPa, whereas we employed a maximum stone pressure of 0.5 MPa. Using a low stone pressure and fine abrasive grains, we achieved crack-free super-finishing of borosilicate glass, even a small-sized machine was used. By using a stone pressure of 0.1 MPa, we could obtain a surface finish of 4 nm Ra with the #8000 grindstone (mean grain diameter of 1 μm).

Fig. 5 Variation of surface finish with stone pressure

Fig. 6 SPM of finished surface

4. Environmental impact assessment

4.1. Life cycle assessment

Life Cycle Assessment (LCA), a method that quantitatively evaluates environmental impact in the life cycle of the excavation of material used for a product, fabrication, transfer, usage, and disposal, is the standard for measuring the contribution level of sustained economic development. As prescribed in ISO14042, LCA consists of the following four elements: Goal and scope, Life cycle inventory, Life cycle impact assessment, and Interpretation. We make a function of the object product and the standard to clearly conduct LCA by setting the goal and scope. Next, we decide the range of the process related to the life cycle of products and investigate environmental load.

A life cycle inventory quantifies the composition of spent resources and the material discharged to the environment in correspondence with matter whose goal and scope was determined. We analyze conduct analysis based on the data (basic unit) for each process in the product's life cycle, the raw materials, the energy consumption, and the material's discharge into the environment. We also calculate the gross weight of a material lost to the environment and show the calculation type in Eq. (1).

$$\text{Gross weight of lost material} = \Sigma(\text{quantity of natural resource used} \times \text{basic unit}). \quad (1)$$

The life cycle impact assessment evaluates the environmental influence and determines a product's influence in a life cycle. Life cycle impact assessment consists of categorization and characteristic analyses. The categorization assigns such environmental impact as the consumed resources or the lost material to the influence domain. Environmental problems include global warming, acidization, eutrophication, and resource consumption. The characteristic analysis calculates an influence index and the product of the value of the gross weight of a lost material by the characteristic coefficient to express the degree of the contribution in the influence domain of the environmental impact. Equation (2) shows the calculation

type.

$$\text{Influence index} = \Sigma (\text{discharged material} \times \text{characteristic coefficient}). \quad (2)$$

With "Interpretation," we estimate the inventory analysis and consider the environmental influence along the setting goal and scope.

4.2. Analysis conditions

In this study, we aimed at evaluating the environmental impact of proposed polishing method by using fixed-abrasive and a small-sized machine, comparing conventional method. Polishing by human work is also attempted to evaluate. Figure 7 shows system boundary, which is taken into account, and the details are described in section 2 and 3. The function unit is set to a process which allows 1 μ m removal. Finished surfaces are assumed to be almost the same by using both of methods. The targets were manufacturing phase and disposal phase, and the recycle was not considered.

(a) Conventional polishing by human work

(b) Proposed polishing with fixed-abrasives

Fig. 7 System boundary

JEMAI-Pro was used as a LCA software. The background data was used from JEMAI-Pro data.

4.3. Result and discussion

Figure 8 shows the power consumption in manufacturing phase with two methods. Energy consumption with small-sized machine is larger than that of human work, which is almost 0 compared to machine work. However, human work is originally eco-friendly. Compared to conventional large size machine, it is clear that the small-sized machine has environmental advantage in mass of machine. This mass connects to the environmental impact directly, so that the small-sized

machine has advantage in phases of manufacturing machine itself and disposal. Decreasing the machine size, the environmental impact will be eco-friendly. However, the process which saves energy the most was the polishing by human work in this study.

Fig. 8 Comparison of power consumption

Figure 9 shows result of global warming potential in disposal phase. This result was paid attention to GWP. The GWP is a relative value of Radiation Effects compared a certain material with carbon dioxide. Generally, heat-trapping gas which influences global warming indicates carbon dioxide, methane, dinitrogen monoxide etc. The GWP in proposed method is greatly reduced in Fig. 9. This is thought that fixed-abrasive reduces the difficulty of fluid disposal by holding abrasive grains on the grindstone. There are some proposals to recycle slurry, but they have not been widespread yet. However, GWP of conventional disposal is not absolutely high. It is thought that the use of required amount of slurry will not increase the environmental impact rapidly. On the other hand, fixed-abrasive method that can yield fine and accurate surface is thought to be still under development.

Here, Fig. 10 shows acidification potential in disposal phase. In Fig. 10, acidification potential of slurry and polisher disposal is larger than that of water lubricant. It is generally said that NO_x affect the acidification potential. Thus, it is thought that the generation of nitrous oxides caused by reclamation disposal of polisher increased, and influenced the acidification potential.

Fig. 9 Global warming potential in disposal phase

Fig. 10 Acidification potential in disposal phase

5. Conclusion

Conventional and proposed polishing process has been drawn attention, and evaluations in manufacturing phase and disposal phase were conducted from the viewpoint of environmental impact and energy. As a result, it was found that polishing by human work was an eco-friendly process, even if it was compared with desktop size machine manufacturing. Moreover, the effectiveness by using fixed-abrasive process has been clarified in disposal phase.

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