OPTIMIZATION OF MECHANICAL INTERFACE FOR A PRACTICAL MICRO-REDUCER

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ABSTRACT

A micro-reducer, which is characterized in its smaller size, higher reduction ratio and higher reliability, has been successfully developed. To improve the mechanical interface (microscopic design and tribology) of such micro-mechanism, configuration, materials, fabrication and surface modification were investigated. Internal energy dissipation of the micro-reducer with two types of bearings and lubrications were measured. Finally the developed micro-reducer, which comprises a 3K-type mechanical paradox planetary gear reduction system and simple gear trains, with oil-lubricated rolling bearing and raw gears was observed to have sufficient performance after 5,000,000 rotations.

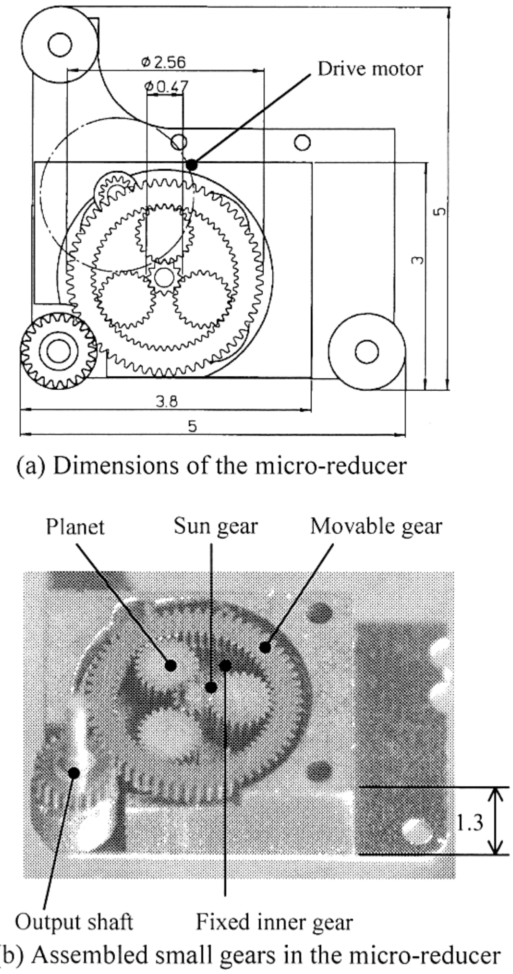
INTRODUCTION

Micromachines are highly expected to maintenance works for power station, etc., as their small bodies are suitable for passing through narrow spaces. However, as it is generally difficult for micro-scale motors to generate such high torque as macro-scale motors, micro-scale reducers are necessary. The micro-reducer can increase the power produced by a high-speed and low-torque micro-motor, but its mechanism is so complicated that mechanical interface is significant to realize a practical micromachine. The requirements of the micro-reducer are for example as follows; its size is within 5 x 5 x 1.5mm cube, the reduction ratio is more than 200, while the output rotation speed of the micro-motor is 40,000 rpm. This paper describes the optimization of mechanical interface for a practical micro-reducer to meet the specifications.

GEOMETRY

To achieve such high reduction ratio as 200, a multiple reduction system is necessary if the micro-reducer consists of only simple gear trains because of the low reduction ratio. The torque transmission efficiency of gear trains is usually high in macro scale. In micro-scale, however, compact and high performance bearings are not available, the structure of many shafts and bearings result in low torque transmission efficiency and difficulties in production and assembly. The micro planetary gear system is a good solution for compactness, because the planetary gear system has an advantage of high reduction ratio per unit volume. It also can decrease the number of shafts and bearings which may cause the increase of friction in micro-scale.

An overall geometry of the novel micro-reducer is shown in Figure 1(a) and 1(b). The size of a reduction part is



(a) Dimensions of the micro-reducer

(b) Assembled small gears in the micro-reducer

Figure 1. Geometry of the novel micro-reducer

approximately 3 x 3.8 x 1.3mm. It comprises a 3K-type mechanical paradox planetary gear reduction system of 115 in reduction ratio and a simple gear train of 4.9 mounted backside. A drive motor is also attached on the backside. The torque is transmitted to the sun gear by the simple gear train, then to the movable gear by the planetary gear system, and to the output shaft. Since the rotation speed of the output shaft is increased after the planetary gear system, total reduction ratio of 201 is finally obtained. The gear module of the gear train and planetary gear system is 0.03, and the final gear trains for output is 0.04. Taking 0.3 as a coefficient of friction, the theoretical torque transmission efficiency in the ordinary scale is about 50%. However, the developed gears' module is so small, and a few reports have been issued about the mechanical performance of such a microscopic gear reduction system[1].

MATERIALS SELCTION

The micro-reducer, in particular micro-gears, should have the characteristics of high resistance to wear for high mechanical reliability and low friction for high transmission efficiency. Friction and wear are serious problems in micro-systems because of the increase of the surface area to volume ratio upon miniaturization. They will obstruct the mechanical performance of the micro-reducer by decreasing the transmission efficiency and reducing the lifetime. The gear materials, therefore, must be chosen with considerations on wear and friction. In this context, metals, engineering ceramics and compound materials are expected for the selection.

There is a rationalized procedure established as an environmentally conscious materials selection methodology[2]. It evaluates the physical properties and environmental impacts of materials at the same time. As functional properties, strength and configuration stability of such small gears were first analyzed by using the fundamental selection methodology[3]. Next, energy content of the materials as an environmental impact and hardness were analyzed to decide the best materials.

Figure 2 shows the properties of the materials suitable for micro-fabrication on specific strength and resistance to thermal distortion as functional performance. The specific strength means the strength (endurance limit) per mass (density) and indicates feasibility to a light and reliable mechanical system. The resistance to thermal distortion is defined as the thermal conductivity per thermal expansion (linear expansion coefficient). This gives a durable precision of micro-gears in thermally hard conditions. Right and upward directions are better materials in both properties. SiC, Cermets, Si, Si_3N_4 and High C Steel are relatively good. Figure 3 is the chart for environmental performance (strength per energy content) and hardness. Here the environmentally friendly materials means those which consume low energy when they are manufactured. Better materials in both aspects are SiC, SiO_2, Si_3N_4, Cermets and High C Steel.

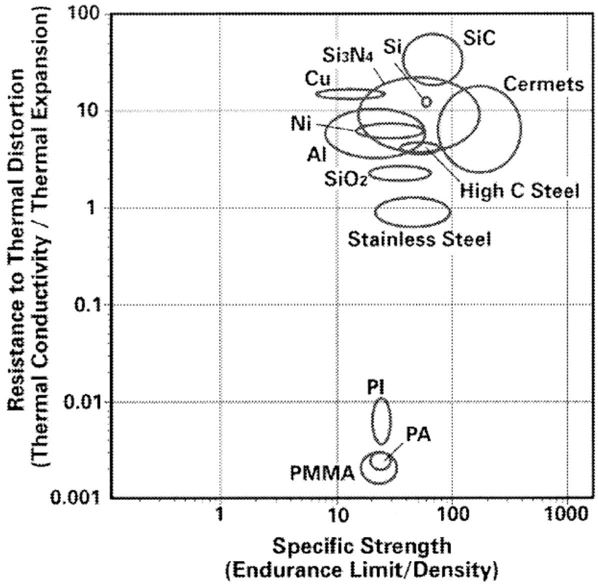


Figure 2. Chart of material properties for specific strength and resistance to thermal distortion

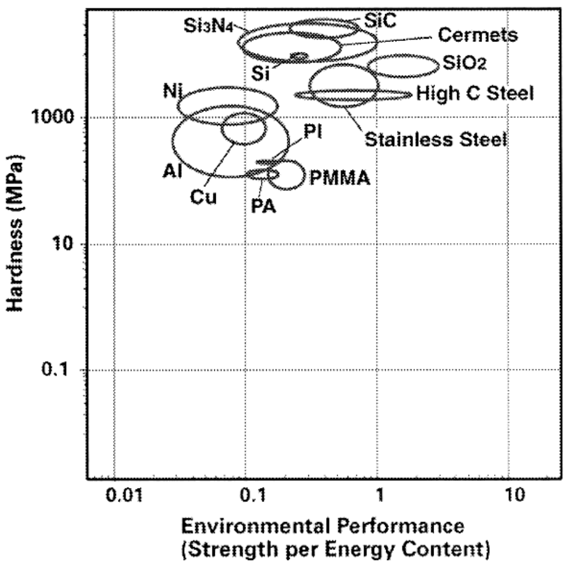


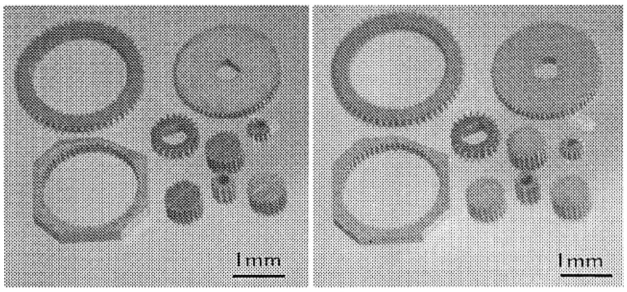
Figure 3. Chart of material properties for environmental performance and hardness

As micro-gears are fabricated by micro electro-discharge machining (micro-EDM) in this research, special kinds of Cermets or High C Steel are candidates from the mechanical, thermal and environmental attributes.

Cermets are the strongest and have high resistance to thermal distortion, but generally brittle. If the magnetic force must be minimized to handle such small components, a kind of Cermets will be selected. High C Steel looks better than Cermets if it's poor hardness is overcome. Finally SKS3 tool steel from High C Steel and WC-Ni-Cr super hard alloy from Cermets was selected for the gear materials.

FABRICATION

High accuracy of micro-EDM is suitable for producing such microscopic and complicated components for the micro-reducer. The micro-EDM has another benefit of shaping three-dimensional microstructures from electric conductors. Small gears produced by the micro-EDM are shown in Figure 4. All these gears are necessary for the micro-reducer. The materials of the gears are SKS3 tool steel (left) and WC-Ni-Cr super hard alloy (right). The module of the gear is 0.03 except the movable gear's outer teeth (located at the left upper) and the gear for output shaft (located at the center). Both materials are accurately machined. Figure 5 shows the distribution of shaped gear's dimensional error. The standard deviation is 0.127, and the average value is -0.034. The result shows that the fabrication precision is within 0.4 %. It is already reported that the wear progress of these micro gears is similar to that of the conventional macro gears[4].



SKS3 tool steel WC-Ni-Cr super hard alloy

Figure 4. Small gears made by micro-EDM

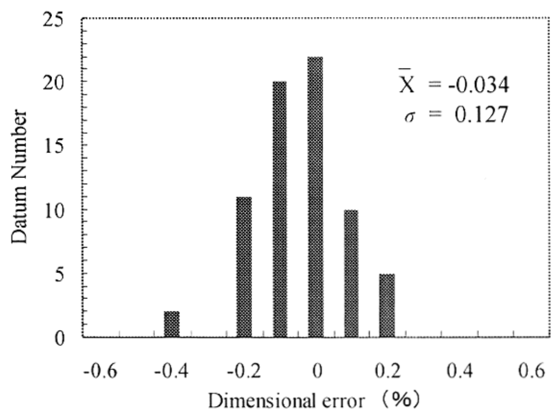


Figure 5. Distribution of gears accuracy

SURFACE MODIFICATION

To improve the surface-based attributes such as hardness and friction coefficient, surface modification was investigated with diamond like carbon (DLC), chromium nitride (CrN) and molybdenum sulfide (MoS_2) thin film deposition. A cross section of the CrN thin film deposited on the planetary gear teeth is shown in Figure 6. It is observed that the thin film traces the grain boundaries of the gear teeth made from tool steel accurately. This is performed by a rotating cathodic arc palsma deposition (CAPD) process. The CAPD process has a lot of benefits such as high film adhesion and density, high deposition rates with excellent coating uniformity, high quality stoichiometric reacted coatings

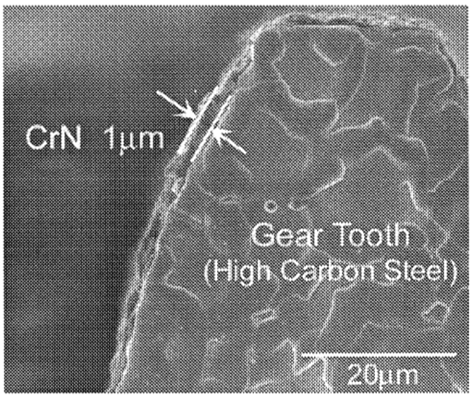


Figure 6. SEM micrograph of gear tooth

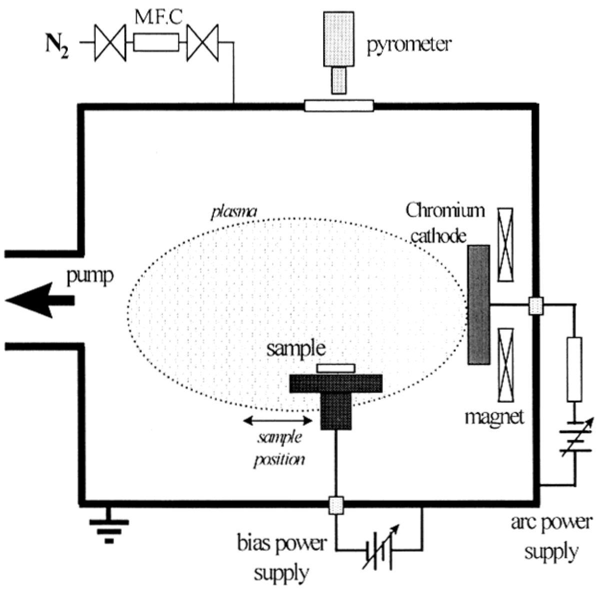


Figure 7. Cathodic arc plasma deposition system

over a wide range of processing conditions and low substrate temperatures during deposition[5]. A schematic illustration of the CAPD system is shown in figure 7.

Hardness of the thin films was measured by micro-Vickers hardness testing with a load of 50g applying 15 seconds. Friction coefficient was measured by using Al_2O_3 ball of 10mm in diameter. Film adhesion was measured by a scratch test. Table 1 shows the results. The surface hardness can be increased by depositing DLC and CrN thin film, and the friction coefficient can be decreased by DLC and MoS_2. Surface modification is expected to increase the suitability of selected gear materials.

Table 1. Effects of film deposition on surface

		Machined Surface	Film Deposition DLC (1 μm)	CrN (1 μm)	MoS_2 (0.3 μm)
Micro Vickers	(Hv)	290	461	582	——
Friction	static	0.27	0.18	0.21	0.19
Coefficient	kinetic	0.10	0.08	0.13	0.07
Adhesion	(mN)	——	480	>828	——

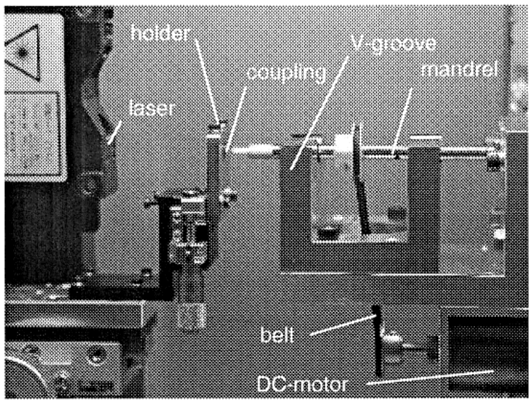
PERFORMANCE

Torque transmission performance

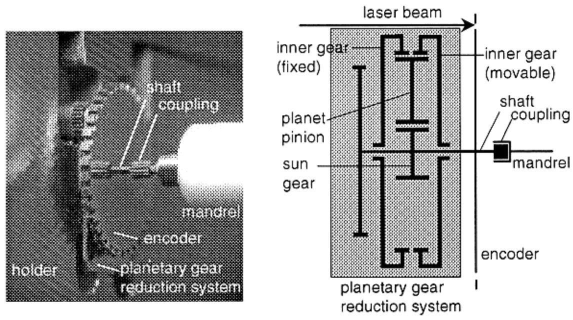
In order to realize a high performance planetary gear reduction system, the bearing configuration of the shaft and the less friction on gear surface are considered to be the most important factors. The torque transmission performance of the planetary gear reduction system was evaluated using a new measurement technique to estimate the internal energy dissipation.

The test apparatus is shown in Figure 8. The planetary gear reduction system is mounted in the holder to be driven by the DC-motor through the belt, the mandrel and the coupling. The rotation of the shaft is measured by using the optical encoder which detects the reflected laser beam from the surface of the encoder. Then the driving force is suddenly disconnected at the coupling. The damping behavior of the remaining free rotation of the shaft reveals the internal energy dissipation of the planetary gear reduction system. The kinetic energy E in the reduction system is given by;

$$E = \frac{1}{2} I_e \omega^2 \qquad (1)$$



(a) Set-up to operate and measure the planetary gear reduction system



(b) Enlarged view around the coupling

Figure 8. Test apparatus for torque transmission performance measurement

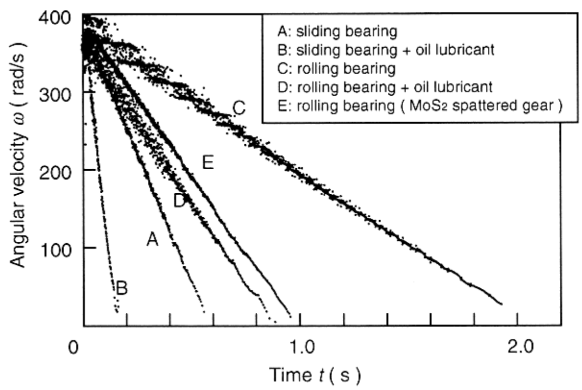


Figure 9. The measured damping behavior for four kinds of lubrication

where ω is angular velocity of the shaft. A set of the moment of inertia of the shaft, the encoder and the gears are all converted to an equivalent moment of inertia I_e around the axis of the shaft. Energy dissipation rate P is calculated from the measured angular velocity ω using the following equation:

$$P = -\frac{dE}{dt} = -I_e \dot{\omega} \omega \qquad (2)$$

The energy dissipation rate in case of sliding bearing and rolling bearing are tested. The effect of oil lubrication is examined for each bearing system. The MoS_2 lubrication is also examined using MoS_2 spattered planetary gears with ball bearing in dry condition. The measured angular velocity of the shaft is shown in Figure 9. The rotation of the shaft continues longer with a rolling bearing and no lubricant and shorter with a sliding bearing and oil lubricant. MoS_2 spattered gears play the same role as the oil. The energy dissipation rate of the planetary gear reduction system calculated from equation (2) is shown in Figure 10. These results are showing that the rolling bearing is still advantageous in this microscopic mechanism, and both bearing systems in oil condition (B,D) waste more energy than those in dry condition (A,C). The MoS_2 film on gear teeth (E) does not decrease the internal energy dissipation rate. This result shows rolling bearing is better than sliding bearing and even in case of sliding bearing non lubrication is better for high transmission efficiency.

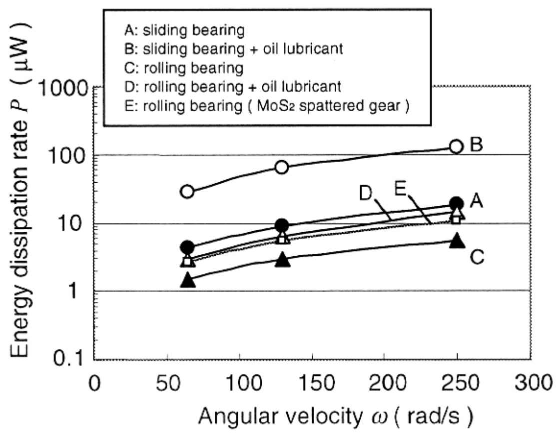
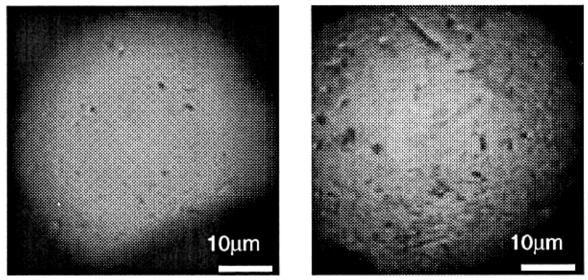


Figure 10. Internal energy dissipation rate of the micro-reducer

Durability

The durability of the rolling bearing without lubrication was also examined. The planetary gear reduction system is driven by a micro-motor which produces the torque of 10^{-7} Nm. After 100,000 shaft rotations, the internal energy dissipation rate increased too much for the micro-motor to overcome. Figure 11 shows the comparison of dimples on the rolling ball's surface observed before and after 100,000 rotations. The condition of the ball bearing with oil lubrication is a solution for a long term durability.

The lifetime of the micro-reducer was evaluated by comparing the change of internal energy dissipation rate before and after rotation. An oil-lubricated rolling bearing is adopted due to its durability, and raw or MoS_2 spattered planetary gears are experimented. Figure 12 shows the relation between rotations and internal energy dissipation rate. The internal energy dissipation of both gears decreases until 100,000 rotations, then increases. With reference to the MoS_2 spattered planetary gears, the internal energy dissipation rate after 500,000 rotations became so large that the experiment was stopped. It was observed that a part of the MoS_2 film has worn off and gathered to the gear center. On the contrary that of the raw planetary gears did not exceed the initial value up to 5,000,000 rotations.



(a) Before rotation (b) After 100.000 rotations

Figure 11. The ball's surface of rolling bearing without lubrication

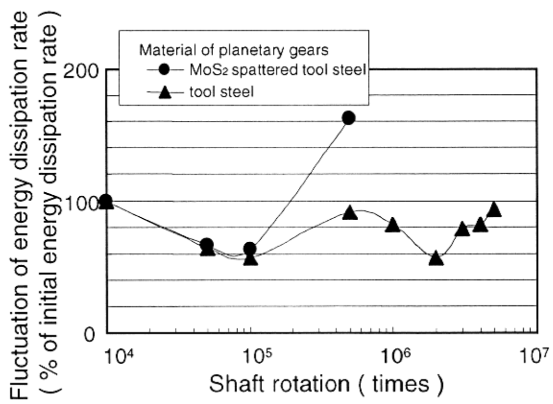


Figure 10. Fluctuation of internal energy dissipation rate during a long term operation

CONCLUSION

A synthetic optimization method on mechanical interface to realize a practical micromachine was investigated. With the results a new type of MEMS element called a micro-reducer has been successfully developed. The micro-reducer can enlarge the torque of micro-motors with the higher feasibility.

The reduction mechanism was based on the 3K-type mechanical paradox planetary gear reduction system due to its compactness and easy assembly. SKS3 tool steel and WC-Ni-Cr super hard alloy were selected for the gear materials due to their excellent mechanical, thermal and environmental properties. The main components were machined by the micro-EDM due to its high precision. Deposition of DLC and CrN thin film on tool steel improved the hardness, and DLC and MoS_2 decreased the friction coefficient.

The torque transmission performance of the planetary gear reduction system was also evaluated by a new measurement technique. It was understood that rolling bearing is better than sliding bearing and even in case of sliding bearing non lubrication is better for high transmission efficiency. Finally the developed micro-reducer with oil-lubricated rolling bearing and raw gears was observed to have sufficient performance after 5,000,000 rotations. This gives a perspective of great progress and many applications to MEMS elements.

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