Printed gear sensor for health monitoring
(Development of three-axis laser printer for conductive ink and evaluation of laser-sintered electric circuits)

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Abstract
This article intends to discuss the possibility of how to quickly improve the functions of in-situ sensing gear conditions. This study proposes a new manufacturing method of the sensors by using a laser beam machine sinters conductive inks sprayed on gear surfaces as a crack sensor. For this purpose, we have developed a three-axis laser-printing machine. The developed three-axis laser printer was based on a three-axis CNC machine, and a 1.6W laser module (445nm wave length) was mounted on the principal axis of the CNC machine. However, the laser power was not enough for sintering the conductive ink sprayed on a 5-micrometer-thick polyimide as an insulated layer on steel plates. Thus, the 1.6W laser module is replaced with a 3.5W laser module, which has the same wavelength. This paper shows laser sintering conditions for the new laser module. In addition, a simple sensor, which is able to detect cracks at roots of gear teeth, is proposed. The sensor is formed of an involute spur gear. The electrical property, such as resistance, of the proposed crack sensors was investigated in this paper, and it was concluded that the relation between the resistance and module of gears was linear, when the number of teeth was fixed.

Keywords: Gear sensor, Printed sensor, Conductive ink, Three-axis printer, Laser sintering

1. Introduction

Nowadays, many machines have some sensors, which enable physical conditions, for instance, acceleration, deformation, temperature, etc., to be measured. These measured parameters can be used to modify the desired conditions for the machinery operation or to detect failure signs for appropriate maintenance and safety. However, some measurements of machine elements cannot be done by conventional techniques due to space limitation for measurements, geometric complexity of the elements, operation conditions, such as high rotating speed and more. Specifically, gears have the geometric complexity, and rotate at high speed in the gearbox, and hence it appears that measurement of gear conditions is difficult (Dempsey et al., 2007). Indeed, methods for achieving data acquisition of gear conditions, such as sticking strain gages at the root fillet of gear tooth or installation of accelerometers on gears for vibration measurement, have been studied, but these measurements are limited to large size and targets only in laboratories (Utagawa, 1958, Umezawa, 2000).

On the other hand, rapid prototyping tools, with a wide range of different techniques aided by using 3D-CAD software, offers the possibility to quickly fabricate parts, such as mechanical elements, electronic circuitry, and so on (Mahindru at al., 2013). This rapid prototyping tools are very attractive for many engineers and researchers. Moreover, despite the low accuracy or reliability for some applications, the rapid prototyping tools are friendly with the environment and less expensive for high-mix low-volume or pilot production compared with other manufacturing
techniques, thus, these techniques are gradually being implemented in the industry and increasing user expectations (IHI Technical Report, 2015).

Our interest lies in “printed electronics”, which is the technology to create electronic circuits, such as sensors or antennas on flat planes, by printing conductive inks (Sprules et al., 1996, Daniel et al., 2010, Kawahara et al., 2013). This technology has now lower integration density and is not as competitive as other technologies used for electronics manufacturing, such as, vacuum deposition, photolithography. However, this technology has apparent advantages, such as simple fabrication, low energy consumption and low cost. Therefore, research and development in the field have a growing tendency and companies are releasing new formulations of conductive inks (Terada et al., 2012).

The present study focuses attention on development of new sensor systems for achieving direct-data-acquisition of gear conditions. It is intended that the conductive ink is directly printed on the complex mechanical elements for developing new sensor systems. However, a typical printing machine has only capable of printing in two-dimensional plane (Terada, 2008, Kawahara et al., 2013). For printing the ink on more complex shapes such as gear surfaces, the printing tool should be implemented into numerically controlled multi-axis machine tools. Then, we have developed a 3-axis printing system to print the conductive ink on the surface of mechanical components covered by a polyimide layer (Rodriguez et al., 2015, Iba et al., 2016 a, 2016 b). The developed 3-axis printer consists of a 3-axis CNC machine tool and a laser module. A laser sintering technology of conductive ink is used for printing circuits (Yamazaki et al., 2012). After spraying the conductive ink on mechanical elements, such as gears and shafts, the laser beam sinters a portion of the sprayed ink to manufacture electrical circuits, and then, unnecessary ink on the elements is washed away by acetone. In case of the laser sintering technology, the focal distance of the laser is long in comparison with the distance of inkjet head to object plane (Zöllmer et al., 2012), so that it does not require approaching its head to the complex surface of mechanical components. This manufacture method would be very suitable for manufacturing sensor systems on complex mechanical elements, such as gears. So far, we have clarified the sintering condition of the conductive ink on 60 µm thickness polyimide tape sticking on steel plates (Iba et al., 2016 b). The laser used was 1.6 W and 445 nm wavelength. However, the laser power was not enough for sintering the conductive ink sprayed on a 5 µm thickness polyimide as an insulated layer on steel plates.

Thus, in this paper, the 1.6W laser module is replaced with a new 3.5W laser module, which has the same wavelength, and the laser sintering conditions for the new laser module is shown. Firstly, the focal distance and laser power for laser sintering are investigated. Then, it is shown that the laser head distance to object planes have an appreciable effect on the electrical property, such as resistance. Additionally, a simple sensor, which is able to detect cracks at tooth roots of spur gears, is proposed. The sensor is formed of an involute spur gear. During gear operation tests, the default resistance of sensors may vary with time depending on meshing numbers. At the end of gear operation tests, the sensor resistance should reach an infinite value due to fatigue crack formation. In this paper, the default electrical property of the proposed crack sensors is investigated when changing the module of sensors and the relation between the default resistance and module is shown.

2. Experimental equipment
2.1 Conductive ink

There are various types of conductive ink, for example, a water-soluble solvent or organic-soluble solvent type and silver, cupper or gold Nano-particles type, etc., because printed technology is lively technology. Firstly, newly developed conductive ink, which has water-soluble solvent with silver-Nano-particles developed by Kawahara et al. (Kawahara et al., 2013), was tried for printing gear sensors. This ink was developed for circuit printing with commercially available inkjet printers, and the printed circuits has conductivity after solvent drying. We had developed a three-axis inkjet printer, which had an inkjet cartridge (HP C6602) installed to the principal axis of a three-axis CNC machine, for printing this ink. It was possible to print the ink on PET films, the ink, however, has bad chemistry with polyimide (PI), which has excellent mechanical and thermal properties and is used for an insulated layer of circuits. Thus, we needed another conductive ink, which could be printed on PI.

We listed some types of commercially available conductive ink, which can be available for printing on PI, and selected silver nanoparticle paste of NPS-J (Harima Chemicals, Inc.), which was proven by another researcher (Terada, 2008). The specifications of the ink are, solvent: Tetradecane, conductivity: 3 μΩ·cm, viscosity: 5 to 10 mPa·s, silver particle size: 3 to 7 nm, contain of silver particle: 60 wt%. After curing process for 60 min at 210-220°C, the conductivity is obtained.
2.2 Laser module

To print the selected ink, we had developed ink-jet and dispenser type printers (Rodriguez et al., 2015). However, in the case of these type printers, the print heads had to be brought into the printing objects, closely. These methods do not necessarily relevant to the print of the conductive ink on concave face of gears. Thus, we altered the ways of inkjet and dispenser to the way of laser sintering proposed by Yamazaki et al. (Yamazaki et al., 2012). In the paper, they used 4 different wavelengths of laser (488 nm, 532 nm, 980nm and 1,064 nm) and showed that the smallest wavelength could sinter the narrowest line. They also investigated the absorption spectrum of the conductive ink; NPS-J. The paper showed that the absorption spectrum was under 600 nm, and the peak of spectrum was around 420 nm. It means that a laser module, which has the peak-neighbor wavenumber, enable the ink to be sintered well. According to this result, we selected a laser module, which had 445 nm wavelength and 1.6W power. In our previous research, we showed this new developed laser type three-axis printer. The developed three-axis laser printer was based on a three-axis CNC machine, and the laser module was mounted on the principal axis of the CNC machine (Iba at al., 2016 b). The output power of the laser module was controlled by a PWM signal generated by a microcomputer. The laser beam of 10% duty ratio of the PWM signal could sinter the conductive ink sprayed on 60 µm thickness polyimide tape (commercially available) attached to an SPCC plate. However, when printing the same ink on 5µm polyimide layer manufactured on an SPCC plate, the ink was not sintered and did not have conductivity, although the laser beam of 100% duty ratio of the PWM signal was used. We thought the laser power was not enough for sintering the ink. Therefore, in this paper, the 1.6W laser module is replaced with a 3.5W laser module, which has the same wavelength. In Section 3, we show laser-sintering conditions of the new high-power laser module that can manufacture sintered circuit lines with stability.

2.3 Three-axis laser printer

The laser module is mounted on the principal axis of a three-axis CNC machine to form the three-axis laser printer. Table 1 shows the specifications of the three-axis CNC machine (Original Mind KitMill BT100). Figure 1 shows the developed three-axis laser printer. This three-axis CNC machine has 0.78 µm resolution, and the maximal feeding speed is 15 mm/s. G-code of CNC program (M03), which is originally for the command of spindle rotation, controls the on-off signal of the laser module. This switch signal is transmitted to a microcomputer embedded on the new controller. The microcomputer generates a PWM signal depending on the desired laser power from 0% to 100% and controls the laser module in accordance with the on-off signal.

Fig.1 Developed three-axis laser printer. This laser printer consists of a three-axis CNC machine, blue diode laser module and controller. The laser power is 3.5 W and the wavelength is 445 nm. The three-axis CNC machine has 0.78 µm resolution, and the maximal feeding speed is 15 mm/s.
Table 1. Three-axis CNC machine (Original Mind KitMill BT100)

| Parameter                        | Value    | Unit  |
|----------------------------------|----------|-------|
| Overall size (W × D × H)         | 355 × 300 × 371 | [mm]  |
| Table size (W × D)               | 150 × 100 | [mm]  |
| Maximum height of work           | 42       | [mm]  |
| Stroke (X × Y × Z)               | 154 × 105 × 50.0 | [mm]  |
| Fast forward speed               | 15       | [mm/s]|
| Resolution (Open loop control)   | 0.78     | [µm]  |

2.4 Printing target and printing procedure of conductive ink

Test print targets for the conductive ink are 1 mm thickness cold-rolled-steel plates (SPCC), which are insulated by 60 µm thickness polyimide tape. Figure 2 shows the flow chart of the fabrication procedure of laser sintered electrical circuits on the insulated SPCC plates proposed by Yamazaki et al. (Yamazaki et al., 2012).

![Fig.2 Printing procedure of conductive ink.](image)

After attaching the polyimide (PI) tape on steel plates, the conductive ink is splayed with an airbrush on the insulated plates. Then, the plate is rotated at 1000min⁻¹ for 1 min on a disk to form a homogenous ink layer. Moreover, the coated ink is dried on a hot plate for a short time (1 min at 100°C). Finally, the principal axis of the CNC machine is translated along designed circuit patterns under the laser. The sintering condition of the new high-power laser module is determined through next experimental tests.

3 Laser sintering conditions for conductive ink

In this section, we show laser-sintering conditions of the new high-power laser module that can manufacture sintered circuit lines with stability.

3.1 Focal distance

The laser sintering conditions are shown as follows; Firstly, the focal length of the new laser module, which has 3.5 W output power, is uncover. For this sintering experiment, SPCC plates on which 60 µm thickness polyimide tape is taped are used. The conductive ink is sprayed on the polyimide surface, after that, the conductive ink is sintered with changing distance of the laser module. Table 2 shows the experimental conditions (feeding speed, laser module configuration from object and laser power). In this experiment, a couple of different type duty ratio of PWM signal, 3% and 5 %, is used, and the distance between the laser module and the SPCC plates is changed from 36.5mm to 42mm every 0.5mm. The feeding speed is fixed at 240mm/min. These conditions are decided by reference to the results of 1.6W laser module tests (Iba et al., 2016 b). In the tests, 10% duty ratio of PWM signal for 1.6W laser module, 40 mm distance and 240mm/min feeding speed were suitable and able to sinter the conductive ink with stability.

In addition, the pattern of electric circuit printed in the experiment is 10 mm straight line. Figure 3 shows the relationship between the electric resistance of the laser sintered circuit pattern and the distance between the laser module and SPCC plates.
Table 2. Experimental condition for laser sintering

| Parameter                  | Value | Unit  |
|----------------------------|-------|-------|
| Feed                       | 240   | [mm/min] |
| Distance                   | 36.5  ~ 42 | [mm]   |
| Duty ratio of PWM signal   | 3 or 5| [%]   |

Fig.3 Relationship between resistances and laser module distance. 10mm straight lines are printed on SPCC plates. The distance between the laser module and the SPCC plates is changed from 36.5mm to 42mm. 3% and 5% is used for as the duty ratio of PWM signal for changing laser power. 3% duty ratio is not enough for sintering of the conductive ink. In the case of 5% duty ratio, the local minimums are obtained at 38 and 41 mm.

This figure shows the resistance data variability of 3% duty ratio of the PWM signal. It is perhaps fair to say that the 3% duty ratio is not enough to sinter the conductive ink. On the other hands, the sintering results of 5% duty ratio of the PWM signal indicate that the stably sintered electrical circuits are obtained from 37mm to 42mm distance. This result say that this laser sintering technique is very suitable for making circuit patterns on machine elements, which have complex shapes, because the system has the wide focal distance and is able to sinter the ink if the position of the laser module is slightly shifted. Additionally, the minimum resistance was obtained at 38 or 41 mm.

3.2 Effect of duty ratio of PWM on line width

Next, we investigated the effect of laser power on the width of sintered line. For changing the laser power of the new laser module, the duty ratio of PWM signal was changed from 5% to 100%. We also slightly adjusted the laser module position from the printing object to avoid scorched lines. Table 3 shows the result of sintering experiment. In this table, the distances are the minimum value that can avoid scorched lines. Figure 4 shows the relation between the duty ratio of PWM and sintered line width. It is clear that the line width of sintered circuits increases logarithmically with an increase in duty ratio of PWM. It means that we can control the width of sintered lines by changing the duty ratio of the PWM signal.

Table 3. Relation between duty ratio of PWM (laser power) and line width

| Duty ratio of PWM [%] | Sintering distance [mm] | Line width [µm] | Resistance [Ω] |
|-----------------------|-------------------------|-----------------|----------------|
| 5                     | 41.5                    | 103             | 17.1           |
| 10                    | 41.5                    | 138             | 8.9            |
| 20                    | 41.5                    | 233             | 5.4            |
| 30                    | 42.0                    | 338             | 3.5            |
| 40                    | 42.0                    | 339             | 3.3            |
| 50                    | 42.0                    | 357             | 3.2            |
| 60                    | 42.0                    | 390             | 2.7            |
| 70                    | 42.0                    | 428             | 2.5            |
| 80                    | 42.5                    | 478             | 2.1            |
| 90                    | 42.5                    | 501             | 2.0            |
| 100                   | 42.5                    | 524             | 1.9            |
Fig. 4 Relationship between duty ratio of PWM signal and line width. The duty ratio of PWM signal for changing laser power was changed from 5% to 100%. The line width of the sintered circuits increases with an increase in the duty ratio of PWM signal.

4 Gear sensors for crack detection

4.1 Crack detection sensor formed by involute line

Next, we propose a new simple sensor for detection of gear cracks, and print it on SPCC plates by using the above-mentioned conditions. The proposed sensor is for involute spur gears and is designed in accordance with the design method of involute gears, which are generated by standard basic rack type tools and have module \( m \). The specification of the design is shown in Table 4, and figure 5 shows an example of the designed sensor.

| Description                        | Value  | Unit      |
|------------------------------------|--------|-----------|
| Pressure angle                     | 20     | [degree]  |
| Addendum                           | 1.00\( m \) | [mm]      |
| Dedendum                           | 1.25\( m \) | [mm]      |
| Working depth                      | 2.00\( m \) | [mm]      |
| Tip and root clearance             | 0.25\( m \) | [mm]      |
| Dedendum fillet radius             | 0.38\( m \) | [mm]      |

\( m \) is module.

Table 4. Specification of standard basic rack for gear sensors

![Crack detection sensor example](image)

Fig. 5 Example of gear sensor for crack detection. A new gear sensor, which has a simple shape, is proposed to detect gear cracks. The sensor is formed by an involute line, which is generated by a standard basic rack shown in Table 4. In this figure, the heavy black line is a spur gear whose module and number of teeth are 1 and 28. The narrow black line is the designed gear sensor whose module is 0.975.
4.2 Relationship between electrical characteristics and module of crack detection sensor

The proposed sensors will be printed on the end faces of spur gears of interest and will be used for condition monitoring of the gears by measuring the resistance change during operation tests in the near future. For this purpose, understanding of default resistances of the printed sensors is extremely important. To obtain the default resistance information, we designed three types of crack detection sensors as shown in Fig. 6, which had different modules (0.6, 0.8 and 1.0) but the same tooth number. In the left side of this figure, the black parts are the signal interface point for resistance measurement.

![Fig. 6 Three different crack sensors. Three different modules (0.6, 0.8 and 1.0) were prepared to check the nominal resistance of the sensors. The black parts are the signal interface point for resistance measurement.](image)

We carried out sensor printing tests by the laser sintering on SPCC plates. Furthermore, the resistances of the printed sensors were measured, and the printed sensor’s default values expressing healthy condition of gears was uncovered with change in module $m$. Table 5 shows the laser printing conditions for crack detection sensors and the design parameters of sensors. The printing objects were the SPCC plates insulated by the 60µm thickness polyimide tape.

| Parameter                  | Value | Unit   |
|---------------------------|-------|--------|
| Feed                      | 240   | [mm/min]|
| Focus-object distance     | 41.0  | [mm]   |
| Duty ratio of PWM (Max laser power: 3.5W) | 5.0   | [%]    |
| Number of teeth           | 28    | [-]    |
| Module                    | 0.6, 0.8, 1.0 | [mm] |

Table 5. Sintering conditions and sensor parameters

Figure 7 shows a photo of the printed crack detection sensors with different modules on an SPCC plate. The figure shows the part of the electric circuits (sensors) after removing of the excess ink by acetone. It appears that the printed patterns are clear and good conditions.
Fig. 7 Printed-crack-sensors for gears. The sensors are printed on an SPCC plate insulated by polyimide tape. The module of the sensors are 0.6, 0.8 and 1.0, respectively.

Figure 8 shows a visual observation of the sintered sensor’s line with an optical microscope, and Figure 9 shows an example of the cross-section curve measured with the optical microscope. It can be seen that the scorched area is obtained near the center of line in Fig. 8. The laser power should be set slightly lower than the value used in this test. From Fig. 9, it is observed that the maximum width and height of the sintered line are about 344µm and 30µm. As can be seen, the top center of the cross-section has a dent. Probably, this area is the scorched area and sintered enough.

Fig. 8 Optical microscope image of printed line. The scorched area is obtained near the center of line in this figure, because of high laser power. The laser power should be set slightly lower than the value used in this test.

Fig. 9 Cross-section of printed line. The width of the printed line is about 344µm at the bottom, and the maximum height of the printed line is about 30µm.
Figure 10 shows the relationship between the resistance and module of the printed crack detection sensors. The horizontal axis is the module $m$ of gear and the vertical axis is the resistance of the sensors. As can be seen, the relationship between the resistance and module of the printed crack detection sensors is linear. In this figure, the black solid line shows the ideal resistance values, which are calculated by using the results of the focal distance test. In the focal distance test, the sintering line was straight and the length was 10mm. In addition, the line has $8\Omega$ resistance. On the other hand, the ideal length of the crack detection sensor of module 0.6, 0.8 and 1.0 are 103.0mm, 137.2mm and 171.4mm, respectively. From the relation, the resistances of the ideal length are calculated as 82.4Ω, 109.8Ω and 137.1Ω, respectively. However, it is clear that the obtained resistances of the printed sensors are not on the ideal line and lower than the ideal line. When complex profiles are sintered, the feeding speed must be not homogeneous due to changing of the acceleration at corners and be slower than that of the motion of a straight line. Therefore, the sintered line partially must have lower resistance than that of the motion of a straight line, and the equivalent series resistance of whole circuit is smaller than the expected. Thus, for comprehension and estimation of the default resistance values of manufactured sensors, a compensate coefficient would be necessary to print different number of tooth and module in the near future.

![Graph showing the relationship between resistance and module of printed crack detection sensor.](image)

Fig.10 Relationship between resistance and module of printed crack detection sensor. As can be seen, the good correlation between resistance and module are obtained. The black solid line shows ideal resistance values obtained by the focal distance test. In the test, 10 mm straight line has $8\Omega$. For example, the length of 0.6m crack sensor is 103.0mm by design, and the resistance should be 82.4Ω. However, the actual resistance value is under 70Ω.

5. Summary

This study proposes a new method to manufacture sensors, which enable physical conditions of gears to be measured directly. In the proposed method, a laser beam machine sinters conductive inks, which sprayed on gear surfaces, to manufacture the sensors. For this purpose, we have developed a three-axis laser printing machine. This paper showed a focal distance and laser sintering conditions of a new 3.5W laser module. Additionally, a simple sensor, which was able to detect cracks at roots of gear teeth, was proposed. The sensor is formed of an involute spur gear. The electrical property of the proposed crack sensors was investigated and the relation between the property and module was shown. Through experiments, the followings were found;

1. 3.5W laser module has focal distances at 38mm and 41.5mm, when 5% power is used.
2. Sintered straight line width was about 100µm, when 5% power and 240mm/min feeding speed were used.
3. A electrical property of crack detection sensors is linear respect to the module, however, the property is not on the ideal value, thus, a compensate coefficient is necessary for printing sensors with different module and tooth number to understand default resistance value of the sensor.

The purpose of laser module replacement was to show the availability of augmentation of the laser power output
for laser sintering of conductive ink on a thin PI layer. Therefore, additional laser sintering tests on thin PI layers should be carried out with the replaced 3.5W laser module, and the validity will be showed in our next paper. Furthermore, a wireless communication technique, such as an electrical power transmission system, RFID system or Bluetooth system, is necessary to extract the condition of sensor; therefore, an antenna should be developed on gear surfaces in the near future.

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