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# Development of the Kurling Type Non-contact Magnetostrictive Torque Sensor

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We have developed a knurling type non-contact magnetostrictive torque sensor using shot peening process of 250 $\mu$m steel shot media. Further it is reported that advanced shot peening technology using 50 $\mu$m steel shot media makes it possible to make hysteresis-free torque sensor.

**Key words**: *Torque sensor, Knurl, Magnetostriction, Shot peening, Sensitivity, Hysteresis, Hysteresis-free, EPS*

## 1. Introduction

A non-contact magnetostrictive torque sensor using helical knurls (Fig.1) has been developed for the first time by the author and KUBOTA Corporation [1], in which the helical knurls are made by precise roll forming process and finished by applying shot peening after heat treatment of the shaft [2]. We have reported a model of this sensor [1] and an improvement effect on sensor characteristics of shot peening, that is hysteresis decrease and sensitivity increase [2]. In this paper, the mechanism of improvement of sensor characteristics is discussed in detail.

One of potential applications of magnetostrictive torque sensor is EPS (electrical power steering) application of automotive field. In the EPS application, there is an extraordinary severe requirement to the torque sensor. That is the overload capability, i.e. rated measurement torque is usually 10Nm but its permissible overload is beyond 150Nm, sometimes 300Nm is required.

In this paper, the appropriate solution of magnetostrictive torque sensor for EPS application is reported, in which the advanced shot peening technology using 50 micron dia. steel shot media is applied to get hysteresis-free torque sensor. The mechanism of hysteresis–free sensor using 50 $\mu$m dia. steel shot media is discussed.

## 2. Experiment of shot peening effect

Several shaft materials of various Ni contents (Table 1) were used to evaluate the effect of shot peening. Test conditions are as follows: Shaft diameter: 18.6mm, Applied torque: 150Nm, Excitation frequency: 50kHz, Shot peening media: 250 $\mu$m steel ball.

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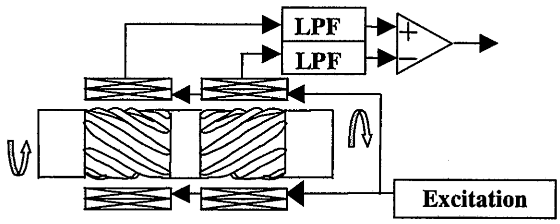


**Fig. 1 Sensor Configuration**

**Table 1 Sensor shaft material composition.**

| Shaft No. | Ni | Co | Cr | Mo | - | Bal |
|---|---|---|---|---|---|---|
| a | 4.3 | | 0.8 | 0.2 | | Fe |
| b | 14. | | 3. | 3. | 1.5Ti | Fe |
| c | 8.5 | | 1. | 1.5 | | Fe |
| d | 18. | 3. | 2.5 | 0.5 | 1.2Al | Fe |

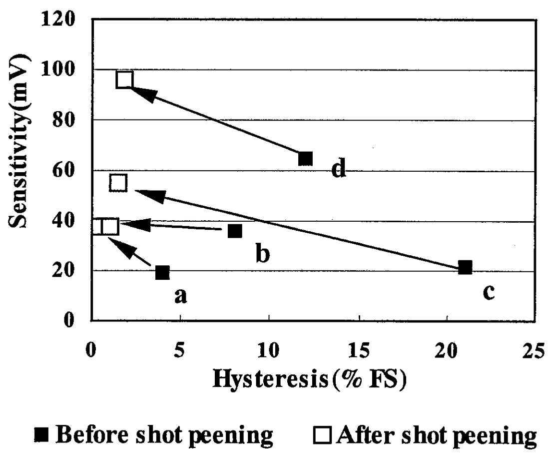


**Fig. 2 Shot peening effect**

Experimental results are shown in Fig. 2. It is found that shot peening to knurls decreases the hysteresis drastically and increases the sensitivity by the factor of 1.5 – 2.5 in most cases, as shown in Fig.2.

## 3. Discussion on shot peening effect

### 3.1 Hysteresis improvement

Fig.3 and Fig.4 show the images of the knurl top regions before and after shot peening, which were taken by an optical microscope (x 400). Specifically, Fig.3 shows a lot of microcrack lines parallel to the direction of knurls, about 10 $\mu$m width, which are produced on the side wall of grooves through the roll forming process of knurls. Fig.4 shows innumerable dents on the knurl surface due to shot peening. It may be concluded that shot peening fixes such surface microcrack lines through collisions of tiny but hard steel balls with high kinetic energy to the knurl surface. Surface microcrack lines restrain the smooth and linear movement of stress flow and magnetic flux flow. Because the skin depth for the materials in Table 1 is about 300$\mu$m at the excitation frequency of 50kHz, improvement of the knurl surface is the most important for the sensor. Hence the hysteresis was reduced drastically.

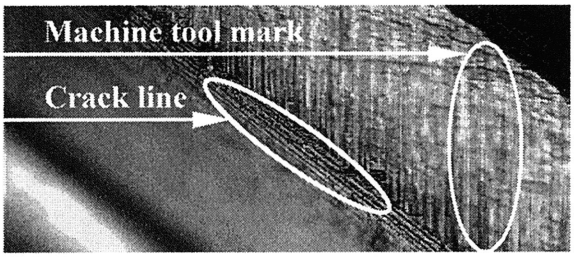


**Fig. 3 Knurl before shot peening (x 400)**

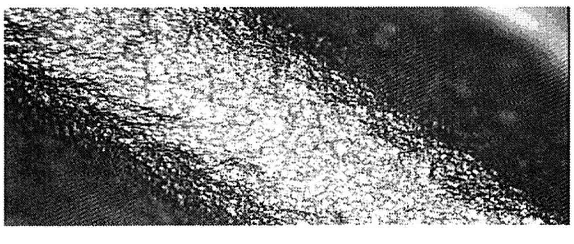

**Fig. 4 Knurl after shot peening (x 400)**

### 3.2 Sensitivity improvement

The effect of shot peening on stress sensitivity of permeability ($\triangle\mu/\triangle\sigma$) was examined, by using a thin oblong plate ($10mm^W$ x $100mm^L$ x $1mm^t$) of the sensor shaft material JIS SNCM 815 (4.3%Ni-0.8%Cr-0.2%Mo-Bal.Fe, sample ("a") of Table 1 and Fig.2). In Fig.5, Y-axis shows the inductance changes ($\triangle L/L_0$, $L_0$= 5$\mu$H: inductance at rest) upon application of tensile stress (100 MPa), which corresponds to the stress applied to the sensors of Fig.1. $\triangle L/L_0$ were measured through the coil winding of 20-turns for un - shot peened sample ("e") and shot peened samples ("f-h"). Measurement frequency of inductance was set at 50 kHz. $\triangle L/L_0$ corresponds to $\triangle\mu/\triangle\sigma$, the so-called "Sensitivity". In Fig.5, X-axis shows shot peening intensity [Arc height[1] (AH)(mmA)]. AH=0 means un-shot peened condition. $\triangle L/L_0$ can be considered as an index representing the sensitivity of a torque sensor made of a corresponding shaft material. Fig.5 shows that the sensitivity ($\triangle L/L_0$) increases with the arc height value and that the sensitivity of sample ("h") with peening intensity AH=0.24mmA is increased by nearly 1.8 times compared to that of the sample without shot peening ("e"). This 1.8 times sensitivity increase of plate sample ("h") is almost the same as 2 times of sensor sample ("a") (SNCM815 in Fig.2). Shot peening intensity AH=0.24mmA applied to the plate sample ("h") is the same shot peening intensity applied to the sensor ("a") in Fig.2.

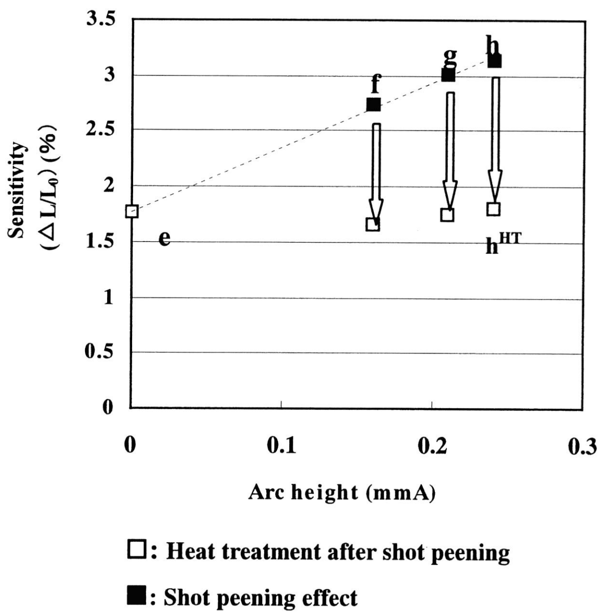


**Fig. 5 Stress sensitivity of permeability**

Shot peening process causes fine dents on the material surface and circular residual stress along the periphery of dents. As it is known the peripheral area of a dent made on a steel plate is subjected to reversible rotational magnetization process because of its circular residual stress along the dent [3]. It is very interesting to note that after applying heat-treatment to the sample "h" at 750ºC, which had exhibited the highest sensitivity, the effect of shot-peening had disappeared; the sensitivity dropped to 1.73% ("$h^{HT}$"), which is very close to 1.76% of sample ("e"). Also when sample "f" and "g" are

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[1] Arc height: When shot peened on one side of thin plate, called Almen Strip A ($18mm^W$×$75mm^L$×$1.3mm^t$), curvature results. This curvature is termed as "Arc height" and corresponds to the shot peening intensity or residual stress of shot peening.

re-heat treated, those sensitivity dropped to 1.7-1.8%. The surface residual stress of each sample measured by X-ray diffractometer was compressive as follows: ("e")=0±62MPa, ("g")= -420±22MPa, ("$h^{HT}$")= -87±11MPa. When shot peened sample ("h") was re-heat treated, the compressive surface residual stress decreased close to that of un-shot peened sample ("e"). Hence we draw a conclusion that shot peening seems to change the sensor magnetization process from (90° +180° ) domain wall displacement and rotational magnetization to rotational magnetization dominant process. Specifically 180° domain wall movement parallel to knurl direction doesn't contribute to magnetostriction and sensitivity. Thus the sensitivity increase could be attributed to the rotational magnetization process, which is made dominant by shot peening through residual stresses.

To show this phenomenon, we investigated the magnetic domain wall movement of 3% Si Fe plate by Bitter method using the colloid of $Fe_2O_3$. Fig 6 shows the image of magnetic domain walls of 3% Si Fe (× 200) without magnetic field. Fig.7 shows the image of magnetic domain wall movement (× 200) with the application of external magnetic field (H=1Oe).

And Fig.8 shows the magnetic domain walls without magnetic field of 3% Si Fe (× 200) around the dimple made by ball pointed pen, which simulates the dimple made by shot peening on the sensor shaft surface. Fig.9 shows the image of magnetic domain wall movement of 3% Si Fe (× 200) with external magnetic field (H=1Oe). Nearby magnetic domain walls around dimple don't move even under the external magnetic field, on the other hand, magnetic domain walls far from the dimple move with the external magnetic field.

So if sensor surface is covered with the dimples made by shot peening, there is no domain wall movement on the sensor shaft surface, but mainly rotational magnetization takes place on the sensor shaft surface.

### 3.3 Summary on shot peening effect

In summary, the shot peening process fixes micro-cracks of the knurls due to roll forming and decreases the hysteresis. Besides that, it changes the magnetization process to magnetic rotation dominant process and increases the sensitivity of the magnetostrictive torque sensor with helical knurls

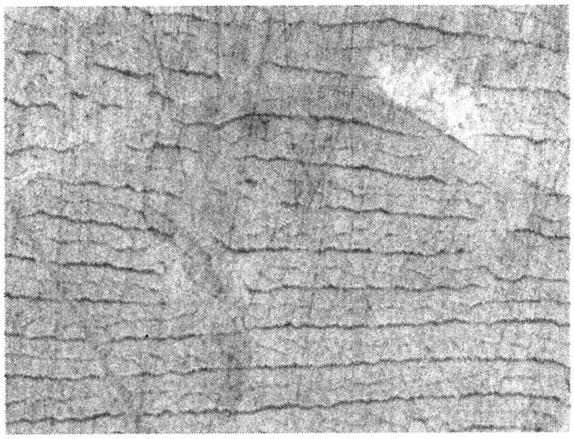


**Fig. 6 Magnetic domain of 3% SiFe (× 200) (No external magnetic field)**

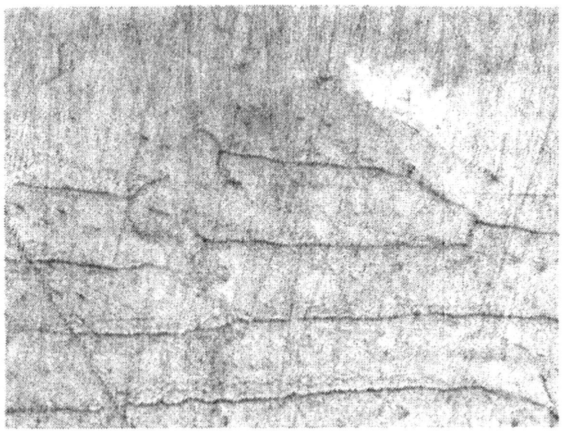


**Fig. 7 Domain movement of 3%SiFe (×200) (under magnetic field H= 1 Oe )**

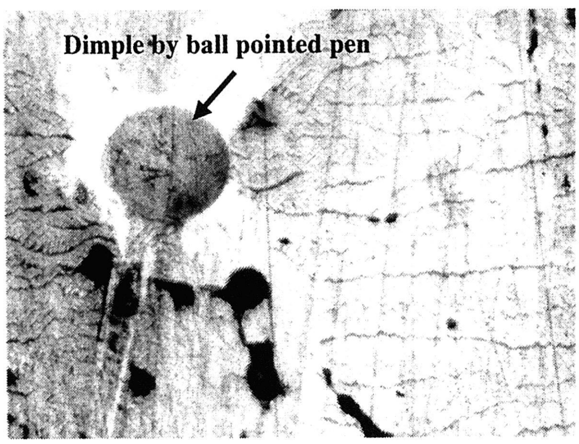



**Fig. 8 Magnetic domain of 3% SiFe around the dimple made by ball pointed pen (No external magnetic field)**

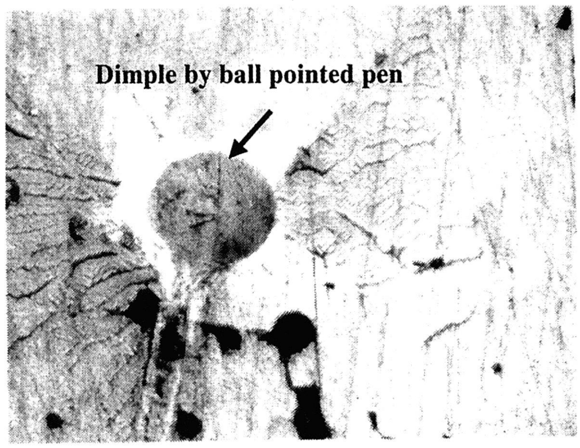



**Fig. 9 Magnetic domain of 3% SiFe around the dimple made by ball pointed pen (under magnetic field H= 1 Oe)**

# 4. Hysteresis-free torque sensor

## 4.1 Need for hysteresis-free torque sensor

One of the most potential applications of magnetostrictive torque sensor is EPS (electrical power steering) application in the automotive field. In the EPS application, there is an extraordinary severe requirement to a torque sensor. That is the overload capability, i.e. rated measurement torque is usually 10Nm which is denoted as FS (full scale), but its permissible overload torque is beyond 150Nm, sometimes 300Nm is required. In this case, hysteresis causes fairly large zero error after overload torque was applied and that poses a problem to this EPS application. In this section, the appropriate solution of magnetostrictive torque sensor for EPS application is reported.

To attain the above mentioned requirement, the direction of sensor hysteresis phenomenon was carefully researched. In this report, CW direction and CCW direction are defined for the hysteresis as shown in Fig.10. We succeeded in appropriately mixing CCW direction hysteresis and CW direction hysteresis in the sensor making process, to get the hysteresis-free torque sensor with ultra - high overload capability, which is needed for EPS sensor. Usually magnetic property, for example, magnetic B-H loop, has CCW direction hysteresis. Oppositely according to our experience, knurled torque sensor shaft has usually CW direction hysteresis property.

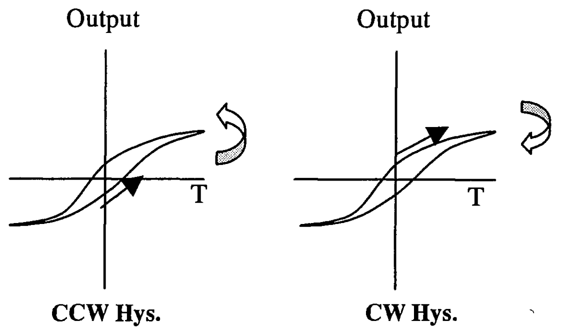



**Fig. 10 Direction of hysteresis**

## 4. 2 Experiment of hysteresis-free sensor

### 4 . 2 . 1 Direction of hysteresis

Following tests were done under the conditions shown in Table 2.

**Table 2 Sensor shaft specification and conditions**

| | |
|---|---|
| Shaft material | SNCM815 (JIS) |
| Shaft diameter (knurl part) | 16.6mm |
| (Roll forming of knurling)<br>Knurling angle to shaft axis<br>Knurling Tooth height<br>Knurling module | <br>45 degree<br>0.5mm<br>0.3333 |
| Rated torque | 10 Nm |
| Permissible overlaod torque | 150Nm |

To compare the CW hysteresis and CCW hysteresis, at first the direction of hysteresis of the sensor, which is single-shot-peened with 250 $\mu$m dia. steel shot media, was measured. That sensor making process is shown in Table 3 (Case 1), which corresponds to Table 1, material "a".

**Table 3 Sensor shaft making process (Case 1)**

| | |
|---|---|
| Heat treatment<br>(cf)(Sensor part is anti-carburized) | Carburization<br>Induction heating |
| Shot peening media dia. | 250 $\mu$m |

Rated torque was 150Nm and hysteresis was measured after 150Nm torque application. Hysteresis vs. exiting frequency is plotted in Fig.11. Hysteresis of this sensor shows only CW direction over the whole frequency range and min. hysteresis can be obtained at the frequency 30-50kHz. Polarity of CW hysteresis is plotted as negative in Fig.11.

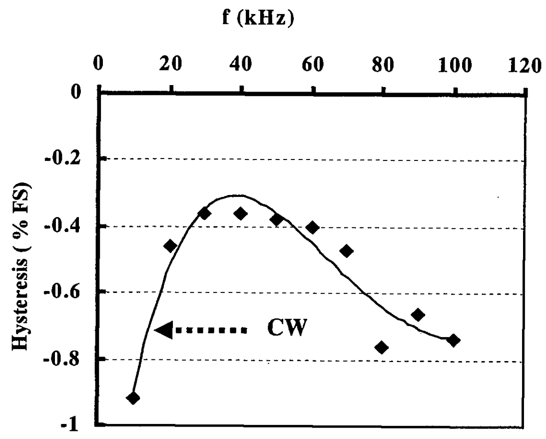



**Fig. 11 Hysteresis by shot peening (250 $\mu$m )**

Next, hysteresis characteristics of another type of sensors were investigated. Three methods, making torque sensor shaft, using 50 $\mu$m dia. steel shot media were investigated (Table 4 (Case 2), Table 5 (Case 3) and Table 6 (Case 4)). Hysteresis characteristics Fig.12, Fig.13 and Fig.14 correspond to Table 4 (Case 2), Table 5 (Case 3) and Table 6 (Case 4), respectively. Rated torque of the sensor was 10Nm and hysteresis was measured after 150Nm overload application. Fig 12, Fig.13 and Fig.14 shows that CW hysteresis appears at low frequency region and CCW hysteresis appears at high frequency region respectively. Fig. 12 (Case 2) shows sensor hysteresis becomes zero at the frequency of 32.5kHz, in other word the hysteresis-free torque sensor could be obtained around at the frequency of 32.5kHz. Fig.13 (Case 3) shows sensor hysteresis becomes zero at the frequency of 126kHz and Fig.14 (Case 4) shows sensor hysteresis becomes zero at the frequency of 156kHz.

Table 4　Sensor shaft making process (Case 2).

| | |
|---|---|
| Heat treatment | Induction heating |
| 1st stage shot peening media dia. | 250 $\mu$m |
| 2nd stage shot peening media dia. | 50 $\mu$m |

Table 5　Sensor shaft making process (Case 3).

| | |
|---|---|
| Heat treatment (cf)(Sensor part is anti-carburized) | Carburization Induction heating |
| 1st stage shot peening media dia. | 250 $\mu$m |
| 2nd stage shot peening media dia. | 50 $\mu$m |

Table 6　Sensor shaft making process　(Case 4).

| | |
|---|---|
| Heat treatment (cf)Sensor part is anti-carburized) | Carburization Induction heating |
| 1st stage shot peening media dia. | 50 $\mu$m |

### 4.3 Discussion on hysteresis-free torque sensor

#### 4.3.1 CW hysteresis

Fig.11 shows the direction of hysteresis after roll forming and heat treatment and shot peening with 250 micron shot media is CW direction over the whole frequency range. We use the roll forming process to make knurling which induces the mechanical defects or flaws into the outermost parts of the sensor shaft. That mechanical flaws seem to be the cause of sensor hysteresis. When there are many mechanical flaws, magnetic domain wall movements upon torque application are pinned at the mechanical flaws, and then when torque is released, those pinned magnetic movements return to its original positions, but over-shoot the original points, that is CW hysteresis, affected by surrounding magnetic movements. Fig.15-1 shows schematically random mechanical flaws induced by roll forming. "D" denotes the depth from the sensor shaft surface and "a" denotes the flaw depth from the sensor shaft surface. When shaft is shot peened, mechanical flaws are fixed and controlled and hysteresis is well controlled under 0.5% FS after 100MPa surface stress upon rated torque application. Fig 15-2 shows the controlled mechanical flaws after shot peening.

#### 4.3.2 CCW hysteresis

On the other hand, hysteresis characteristics of Table 4 (Case 2), Table 5 (Case 3) and Table 6 (Case 4) shows Fig.12, Fig.13 and Fig.14 respectively and each shows the polarity change of hysteresis from CW direction to CCW direction when exciting frequency increases. This big difference between Case 1 and Case 2-Case 4 is that the sensor making process of the latter three includes the shot peening process

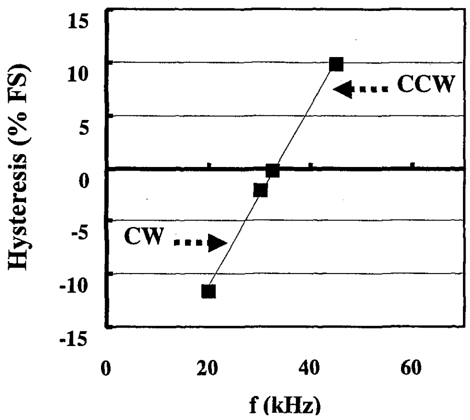



Fig. 12　Frequency dependence of hysteresis

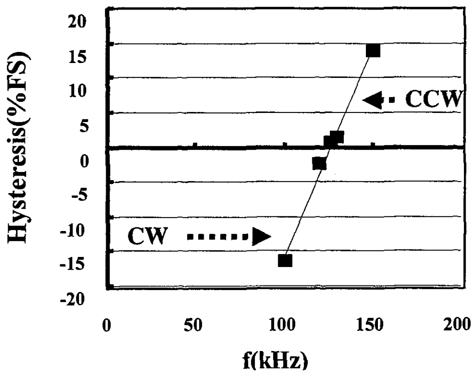



Fig. 13　Frequency dependence of hysteresis

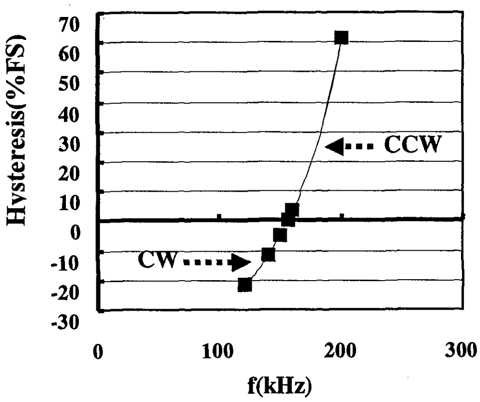
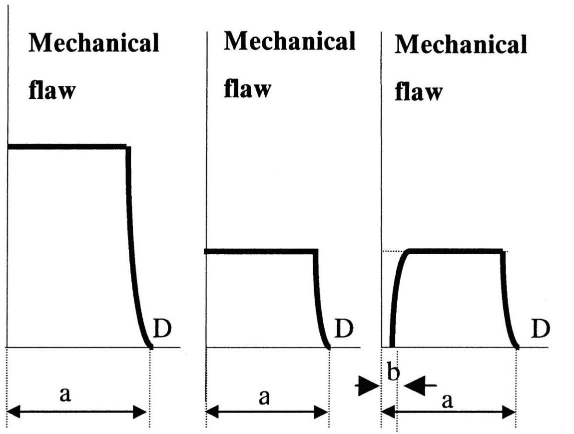



Fig. 14　Frequency dependence of hysteresis

with 50 micron dia. steel shot media. It is reported that shot peening using 50 $\mu$m dia. steel shot media makes the surface of sensor material nanocrystallization.[4)] Nanocrystallization is said to occur when the surface is deformed by the collision of very fine steel ball with high energy. Collision conditions are said as follows: Strain rate of the outermost parts: $3.8*10^{7}(s^{-1})$, Collision power at the surface: $450kJ/s \cdot mm^{2}$, Deformation period: $2.6*10^{-8}(s^{-1})$. The mechanism of nanocrystallization is stated as follows: After big strains with the above said high deformation speed are applied to the surface repeatedly, dislocation density seems to become critical and dislocation cell structures change to crystal boundary structures. In other words, after shot peening with

50 μm dia. steel shot media, sensor outermost parts seems to become flaw-less nanocrystal structure which is the cause of normal magnetization process, or in other words, normal CCW magnetostriction hysteresis. Fig 15-3 shows that recovered surface structure. Recovered depth "b" or in other word, nanocrystallization depth is about 5 μm.[4] That CCW hysteresis characteristics appears at the enough high exciting frequency ( Fig.12, Fig.13 and Fig.14).




| Without shot peening | With Single shot peening (250 μm steel shot media) | With Double shot peening (250 μm +50 μm steel shot media) |
|---|---|---|
| (Fig.15-1) | (Fig.15-2) | (Fig.15-3) |

**Fig. 15 Shot peening effects on hysteresis**

### 4.3.3 Summary on hysteresis-free torque sensor

Shot peening with fairly large diameter steel shot media like 250 μm dia. steel shot media decreases the hysteresis dramatically and its hysteresis polarity is usually CW direction over the whole frequency range.

On the other hand, shot peening with extremely small diameter steel shot media like 50 μm dia. steel shot media changes the direction of hysteresis from CW to CCW with increasing exciting frequency and decreases the hysteresis to zero at the optimum exciting frequency. When exciting frequency is chosen properly and CW hysteresis and CCW hysteresis are mixed properly, hysteresis will becomes zero and hysteresis -free torque sensor can be obtained.

## 5. Torque sensor for a EPS system

Fig.16 shows the developed torque sensor for EPS (electrical power steering) application of automotive field, using double shot peening (250 μm dia. steel shot media +50 μm dia. steel shot media). Sensor making process is Table 4 (Case 2). Its rated torque is 10Nm, permissible overload torque is 150Nm, sensor part dia. is 16.6mm.

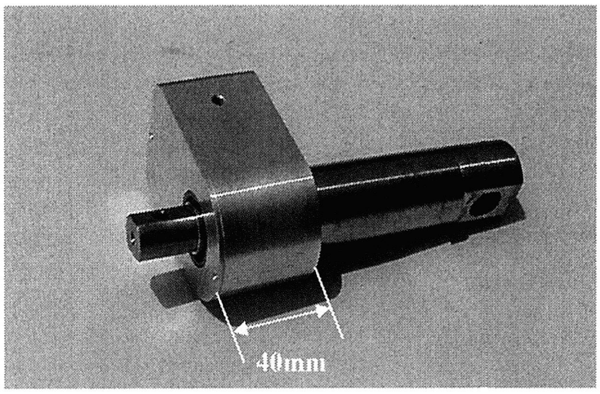



**Fig.16 Torque sensor for EPS**

Fig.17 shows the overload test result. In Fig.17, " ■ " mark shows the application timing of CW overload 150Nm, " ▲ " shows the application timing of CCW overload 150Nm, and " ◆ " shows the zero error amount after the application and removal of overload. The overload test procedure was five cycles of the following sequences.

1)Sensor output measurement before overload.
2)CW 150Nm overload application.
3)Sensor output measurement after overload.
4)CCW 150Nm overload application.
5)Sensor output measurement after overload.
(Repeat 5 times of the above test cycle)

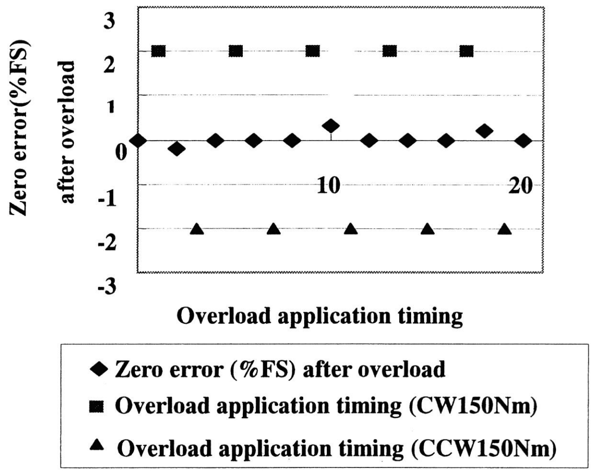



**Fig. 17 Overload capability of hysteresis-free sensor**

Fig. 17 shows only 0.3%FS zero error after overload application of 150Nm, whereas single shot peening process (250 μm steel shot media) gave sensors with more than 5%FS hysteresis after overload application. Other sensor making processes of Table 5 and Table 6 could also have the same good overload capability. This overload capability is enough for the EPS application of automotive field.

## 6. Conclusion

1)Shot peening process dramatically decreases the hysteresis and increases the sensitivity of knurling type torque sensor..
2)Root cause of hysteresis of knurling type torque sensor seems to be micro-cracks on the side wall of knurlings induced during roll-forming process and shot peening process fixes that micro crack. This seems to be the hysteresis improvement mechanism of the shot peening.
3)Sensitivity increase effect of shot peening is attributed to the magnetization process change mainly to rotation magnetization around dimples by shot peening.
4)Evaluation of sensor material and surface treatment can be done very easily by tensile test of thin plate.
5)Hysteresis-free torque sensor can be made by mixing CW hysteresis and CCW hysteresis suitably. CW hysteresis comes from normal sensor making process which is composed of roll-forming of knurling, heat treatment and shot peening with fairy large dia. shot media like 250 $\mu$m dia. steel shot media..
CCW hysteresis comes from shot peening with very fine steel shot media, like 50 $\mu$m dia. steel shot media which makes outermost part structure to flaw-less nanocrystal structure.
6)Possibility of torque sensor for EPS (electrical power steering) application of automotive field was demonstrated by hysteresis-free torque sensor using double shot peening (250 $\mu$m dia. +50 $\mu$m dia. shot media).

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