

## Description

### Low hysteresis sensor

The invention relates to a low hysteresis sensor, such as a current sensor or a position sensor, wherein the current or the position is measured by means of the change in a generated magnetic field in an open magnetic circuit.

Sensors can measure changes of a magnetic field which are caused by an event to be measured. Using one or more flux conducting soft magnetic elements, the generated magnetic field is concentrated at a flux detector located in an air gap in the flux conducting soft magnetic element. Owing to the air gap, the magnetic circuit is open.

The magnetic field may for example be generated by a current or by a movement of a permanent magnet. Depending on the source of the generated magnetic field, the sensor may be a current sensor or a position sensor. DE 100 11 047 A1 discloses a current sensor, while DE 198 25 433 A1 discloses a position sensor; both are based on this measuring principle.

However, sensors of this type have the disadvantage that measuring accuracy is limited by the material hysteresis of the flux conducting soft magnetic element.

DE 42 29 948 A1 discloses a current sensor in which this hysteresis is avoided in order to improve the accuracy of the measurement. This current sensor comprises a single closed soft magnetic core with a primary winding through which the measuring current flows and a secondary winding magnetically coupled to the primary winding via the magnet core.

The magnet core is periodically remagnetised to saturation point, and the voltage drop is sensed, the voltage drop being proportional to the secondary amperage. From the current and preceding values of the voltage drop, an average value is formed, wherein the contributions of the additional magnetisation currents cancel each other. As a result of this periodic remagnetisation of the magnet core to saturation point, independent of the primary current to be measured, the magnetic conditions are

independent of the history of the core in the sensing process. There is therefore no hysteresis.

However, this sensor has the disadvantage of a complicated structure and operation.

The present invention is therefore based on the problem of specifying a sensor which has a simple structure and permits an accurate measurement of a magnetic field generating event, such as an electric current or the movement of a permanent magnet.

This problem is solved by the subject matter of the independent claim. Advantageous further developments form the subject matter of the dependent claims.

The invention specifies a sensor comprising a magnetic field source, at least one flux conducting soft magnetic element with at least one air gap and at least one magnetic field sensor. The magnetic field sensor is located in the air gap and measures a change of the magnetic field of the magnetic field source. The flux conducting soft magnetic element consists in part or wholly of an alloy consisting of  $35\% \text{ by weight} \leq \text{Ni} \leq 50\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Co} \leq 2\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Mn} \leq 1.0\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Si} \leq 0.5\% \text{ by weight}$  and  $0.5\% \text{ by weight} \leq \text{Cr} \leq 8\% \text{ by weight}$  and/or  $0.5\% \text{ by weight} \leq \text{Mo} \leq 8\% \text{ by weight}$ , wherein  $(\text{Mo} + \text{Cr}) \leq 8$ , rest iron and unavoidable impurities.

The change of the magnetic flux of the magnetic field source is caused by an event to be measured. With the flux conducting soft magnetic element, the generated magnetic field is concentrated at the magnetic field sensor in the air gap. The event to be measured may be a flowing current in the case of a current sensor or a movement of a permanent magnet in the case of a position sensor.

As a coercitive field strength is reduced, the material hysteresis of the flux conducting soft magnetic element and thus the sensor hysteresis are increasingly reduced. This results in an increase in sensor linearity. A low sensor hysteresis and an increased sensor linearity result in a more accurate measurement of the magnetic flux which is generated as the permanent magnet is displaced or rotated relative to the flux

conducting soft magnetic element or as the current flows. The accuracy of the sensor is improved by using this alloy for the flux conducting soft magnetic element.

Using a soft magnetic 80% NiFe permalloy involves the disadvantage of a very low saturation below 0.8 T and high material costs due to the high Ni content. The sensor according to the invention at least in part offers a material saturation of more than 0.85 T. In order to minimise the drop in material saturation at elevated operating temperatures, the Curie temperature  $T_c$  should not be too low.

A Curie temperature of the flux conducting soft magnetic element in the range above 200°C enables the sensor to be operated at 125°C. This temperature corresponds to the upper limit of the ambient temperature range of -40°C to 125°C which is typically required in sensors for motor vehicle applications.

The alloy of the flux conducting soft magnetic element therefore offers a combination of properties which are particularly suitable for sensors such as position and current sensors, because their material hysteresis is reduced and the accuracy of the sensor is increased.

Impurities may include O, N, C, S, Mg or Ca or a combination of two or more of these elements and lie below the following limits:  $Ca \leq 0.0025$  % by weight,  $Mg \leq 0.0025$  % by weight,  $S \leq 0.01$  % by weight,  $O \leq 0.01$  % by weight,  $N \leq 0.005$  % by weight and  $C \leq 0.02$  % by weight.

The impurity level may for example be minimised by cerium deoxidation, VIM (vacuum induction melting), VAR (vacuum arc melting), ESR (electroslag refining) or other known processes.

According to the invention, an increased chromium or molybdenum content may result in a further reduction of coercitive field strength. This effect is however dependent on the nickel content of the alloy. If this is too high or too low, there is no significant reduction of coercitive field strength. In addition to iron, the alloy

according to the invention therefore contains 35 to 45 percent by weight of nickel and 0.5 to 8 percent by weight of chromium and/or molybdenum.

The sum of the two elements Mo and Cr is held below 8 percent by weight in order not to reduce the saturation too much.

In further embodiments, the nickel content is defined more precisely, being 38 % by weight  $\leq \text{Ni} \leq 45$  % by weight or 38 % by weight  $\leq \text{Ni} \leq 42$  % by weight.

In further embodiments, 1 % by weight  $\leq \text{Cr} \leq 8$  % by weight and/or 1 % by weight  $\leq (\text{Cr}+\text{Mo}) \leq 8$  % by weight is/are used.

In a further embodiment, the alloy consists of 35 % by weight  $\leq \text{Ni} \leq 45$  % by weight, 0 % by weight  $\leq \text{Co} \leq 2$  % by weight, 0 % by weight  $\leq \text{Mn} \leq 1.0$  % by weight, 0 % by weight  $\leq \text{Si} \leq 0.5$  % by weight and 0.5 % by weight  $\leq \text{Cr} \leq 8$  % by weight and/or 0.5 % by weight  $\leq \text{Mo} \leq 8$  % by weight, wherein  $(\text{Mo}+\text{Cr}) \leq 8$ , rest iron and unavoidable impurities.

The alloy may also contain Mn and/or Si, wherein 0 % by weight  $< \text{Mn} \leq 0.5$  % by weight and 0 % by weight  $< \text{Si} \leq 0.2$  % by weight. Mn and Si can be used for deoxidation, in particular at higher chromium contents.

In a further embodiment, the alloy also contains Co, wherein 0 % by weight  $< \text{Co} \leq 0.5$  % by weight. Co can increase saturation.

In a first embodiment, the magnetic field source comprises a direct current or an alternating current which generates a magnetic field as it flows through a conductor. The magnitude of the generated magnetic field is proportional to the magnitude of the flowing current. The sensor may further comprise at least one winding wound around the flux conducting soft magnetic element. The current to be measured flows through this winding.

In a second embodiment, the magnetic field source comprises a permanent magnet which is movable relative to the flux conducting soft magnetic element. The magnitude of the change of the generated magnetic flux is proportional to the magnitude of the change in the position of the permanent magnet. As a result, the position of the permanent magnet can be determined from the change of the magnetic flux. The permanent magnet can be connected to an object the position of which is to be measured. This may involve a linear or rotary relative movement which is detected by the sensor.

The permanent magnet may have a plurality of areas with alternating directions of magnetisation. These areas may be provided with a plurality of magnets mounted on a yoke. Alternatively, the permanent magnet may be a single unit with varying magnetisation.

The flux conducting soft magnetic element may be shaped in various ways. In one embodiment, a single U-shaped flux conducting soft magnetic element is provided, the gap between the legs of the U being the air gap. In a further embodiment, the flux conducting soft magnetic element comprises several separate parts with an air gap between these parts. The flux conducting soft magnetic element may have one or more slots, each representing an air gap.

In one embodiment, the generated magnetic flux is measured without contact using a magnetic field sensor in the form of a Hall probe. As an alternative, the magnetic field sensor may comprise a strip of amorphous soft magnetic material. A suitable material is commercially available under the trade name VITROVAC from Vacuumschmelze GmbH & Co KG. A magnetic field sensor made of this material is disclosed in EP 0 294 590 A2.

In one embodiment, two or three magnetic field sensors are provided.

Embodiments are described in greater detail below with reference to the drawings.

- Figure 1 is a diagrammatic representation of a first embodiment of a sensor with a flux conducting soft magnetic element made of an alloy according to the invention;
- Figure 2 is a diagrammatic representation of a second embodiment of a sensor with a flux conducting soft magnetic element made of an alloy according to the invention;
- Figure 3 shows the measured coercitive field for alloys with 47 or 37 % by weight Ni and various chromium contents;
- Figure 4 shows the measured coercitive field for alloys with 40 % by weight Ni and various chromium or molybdenum contents; and
- Figure 5 shows the measured coercitive field for further alloys according to the invention.

Figures 1 and 2 show two sensors 1 and 1', each of which comprises a flux conducting soft magnetic element 2 of a soft magnetic alloy with a coercitive field strength of less than 100 mA/cm.

Figure 1 shows a sensor 1 according to a first embodiment, which is designed as a current sensor. Figure 2 shows a sensor according to a second embodiment, which is designed as a position sensor. Both sensors 1 and 1' comprise the component described below.

Each of the sensors 1 and 1' comprises a magnetic field source 3, a flux conducting soft magnetic element 2 with an air gap 4 and a magnetic field sensor 5 located in the air gap 4 and measuring a change of the magnetic flux of the magnetic field source 3. The magnetic field sensor 5 may for example be a Hall probe. The two sensors 1 and 1' differ in the source of the magnetic field.

In the sensor 1 of the first embodiment, a magnetic field is generated by a current 6 flowing through an electrically conductive circuit represented by a wire or a cable.

This magnetic field is guided by the flux conducting soft magnetic element 2 and concentrated at the magnetic field sensor 5 located in the air gap 4. The generated magnetic field is dependent on amperage, so that the amperage can be determined from the measured generated magnetic field. The sensor of the first embodiment is therefore a current sensor.

In the sensor 1' according to the second embodiment, the magnetic field is generated by a permanent magnet 7. The permanent magnet 7 comprises a plurality of areas 8 having alternating directions of magnetisation 9. The direction of magnetisation 9 is illustrated in Figure 2 with reference to the magnetic poles north (N) and south (S).

In the sensor 1' of the second embodiment, the permanent magnet 7 is moved by an object not shown in the drawing. Figure 2 therefore allows for both linear and rotary movement.

The movement of the permanent magnet 7 changes the magnetic field which is concentrated at the magnetic field sensor 5 in the air gap 4 by the flux conducting soft magnetic element 2. The magnitude of the magnetic field changes depends on the extent of the movements of the permanent magnet 7. The position of the object connected to the permanent magnet 7 can be determined from this measured magnetic field. The sensor 1' according to the second embodiment is therefore a position sensor.

The flux conducting soft magnetic element 2 of the current sensor 1 and the position sensor 1' consists of an alloy with a composition described by the following formula:  $35\% \text{ by weight} \leq \text{Ni} \leq 45\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Co} \leq 2\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Mn} \leq 0.5\% \text{ by weight}$ ,  $0\% \text{ by weight} \leq \text{Si} \leq 0.2\% \text{ by weight}$  and  $0.5\% \text{ by weight} \leq \text{Cr} \leq 8\% \text{ by weight}$  and/or  $0.5\% \text{ by weight} \leq \text{Mo} \leq 8\% \text{ by weight}$ , wherein  $(\text{Mo} + \text{Cr}) \leq 8$ , rest iron and unavoidable impurities.

This alloy is an iron/nickel-based alloy with chromium and/or molybdenum. The coercitive field strength of the pure NiFe alloy can be reduced considerably by the addition of the elements chromium and molybdenum, while saturation is more than

0.85 T and thus higher than in 80% NiFe permalloys. This combination of properties results in a reduced material hysteresis. It is therefore possible to produce a sensor 1 or 1' with a reduced material hysteresis and an increased sensor linearity. This improves the accuracy of the sensor 1 or 1' respectively.

Figure 3 shows the coercitive field strength for alloys with 47 and 37 % by weight Ni and a chromium content from 1 to 6.65 % by weight.

The composition, the measured coercitive field and the induction at  $H = 10 \text{ A/cm}$  ( $B_{10}$ ) of these alloys are summarised in Tables 1 and 2. The compositions are given in percent by weight.

|         |      |       |      | 1150°C/H2  |              |
|---------|------|-------|------|------------|--------------|
|         | Fe   | Ni    | Cr   | Hc (mA/cm) | $B_{10}$ (T) |
| 93/4759 | Rest | 47.4  | 0.96 | 24         | 1.39         |
| 93/4760 | Rest | 47.45 | 1.67 | 26         | 1.33         |
| 93/4867 | Rest | 47.4  | 2.17 | 35         | 1.31         |
| 93/4868 | Rest | 47.4  | 3.14 | 28         | 1.228        |
| 93/4869 | Rest | 47.4  | 4.10 | 34         | 1.146        |
| 93/4870 | Rest | 47.4  | 5.05 | 46         | 1.08         |
| 93/4525 | Rest | 47.6  | 6.04 | 31         | 0.99         |

Table 1

|         |      |       |      |      |      | 1150°C/H2  |              |
|---------|------|-------|------|------|------|------------|--------------|
|         | Fe   | Ni    | Cr   | Mn   | Si   | Hc (mA/cm) | $B_{10}$ (T) |
| 93/4444 | Rest | 36.95 | 2.10 | 0.50 | 0.21 | 72         | 1.17         |
| 93/4443 | Rest | 36.95 | 4.15 | 0.5  | 0.2  | 60         | 1            |
| 93/4442 | Rest | 36.95 | 6.65 | 0.5  | 0.22 | 42         | 0.81         |

Table 2

In the comparative embodiment of Table 1, the alloy contains approximately 47 % by weight Ni. With this nickel content, there is no correlation between chromium content and coercitive field. At a lower nickel content of approximately 37 % by weight, the

coercitive field is reduced from more than 70 mA/cm to approximately 40 mA/cm as the chromium content increases.

Figure 4 shows two embodiments of an alloy for the flux conducting soft magnetic element 2 of the sensor 1 or 1' respectively, each containing 40 % by weight Ni. 2 and 4 % by weight Cr are added to the first embodiment and 2 and 4 % by weight Mo are added to the second embodiment. In both cases, the coercitive field strength is reduced as the chromium and molybdenum content increases.

Table 3 summarises the compositions and values of  $B_{10}$ ,  $H_c$  and  $T_c$  (Curie temperature) for further alloys from which the flux conducting soft magnetic element 2 of the sensor 1 or 1' can be made. The values of the coercitive field strength  $H_c$  of these alloys are also represented graphically in Figure 5.

| Fe   | Ni (% w/w) | Cr (% w/w) | Mo (% w/w) | $B_{10}$ (T) | $H_c$ (mA/cm) | $T_c$ (°C) |
|------|------------|------------|------------|--------------|---------------|------------|
| Rest | 36.1       | 2.1        |            | 1.05         | 72.9          | 164        |
| Rest | 38.0       | 3.3        |            | 1.10         | 59.3          | 184        |
| Rest | 40.1       | 2.1        |            | 1.33         | 51            | 248        |
| Rest | 40.0       | 4.5        |            | 1.09         | 37.4          | 208        |
| Rest | 40.0       | 5.8        |            | 0.99         | 32            | 187        |
| Rest | 40.0       | 7.1        |            | 0.87         | 30.2          | 164        |
| Rest | 43.0       | 5.8        |            | 1.02         | 31.1          | 248        |
| Rest | 44.0       | 4.5        |            | 1.15         | 32.6          | 291        |
| Rest | 44.0       | 5.8        |            | 1.05         | 35.5          | 270        |
| Rest | 44.0       | 7.1        |            | 0.95         | 38.7          | 248        |
| Rest | 40.0       |            | 1.9        | 1.30         | 36.5          | 279        |
| Rest | 39.9       |            | 4.3        | 1.15         | 31.5          | 277        |
| Rest | 41.7       |            | 5.5        | 1.12         | 36.5          | 316        |
| Rest | 40.0       | 2.2        | 2.1        | 1.12         | 30.6          | 243        |

Table 3

The air gap 4 in the flux conducting soft magnetic element 2 results in a shearing of the magnetic circuit, i.e. the hysteresis loop measured at the flux conducting soft magnetic element 2 becomes flatter the wider the air gap 4 is.

The coercitive field strength  $H_c$  of the soft magnetic material determines the remanence of the loop in the open magnetic circuit. This directly affects the hysteresis and thus the accuracy of the sensor 1 or 1' respectively. By using an FeNiCr material according to the invention with a low coercitive field strength, the sensor hysteresis can be reduced.

In sensor applications, soft magnetic materials are for example used as flux conducting soft magnetic elements or flux concentrators. As a rule, sensors are required to map an input value into a sensor signal in as linear a manner as possible. For the soft magnetic material, this means a low coercitive field strength and thus a low hysteresis.

Saturation should not be caused to drop by more than 30% between room and maximum temperature by the ambient temperature of the sensor application, e.g.  $-40$  to  $125^{\circ}\text{C}$  in sensors for motor vehicles.

## List of Reference Numbers

- 1 Current sensor
- 1' Position sensor
- 2 Flux conducting soft magnetic element
- 3 Magnetic field source
- 4 Air gap
- 5 Magnetic field sensor
- 6 Current
- 7 Permanent magnet
- 8 Area of permanent magnet
- 9 Direction of magnetisation

## Patent Claims

1. Sensor (1; 1') comprising:  
a magnetic field source (3),  
at least one flux conducting soft magnetic element (2) with at least one air gap (4) and at least one magnetic field sensor (5) located in the air gap (4) and measuring a change of the magnetic field of the magnetic field source (3),  
characterised in that  
the flux conducting soft magnetic element (2) consists of 35 % by weight  $\leq$  Ni  $\leq$  50 % by weight, 0 % by weight  $\leq$  Co  $\leq$  2 % by weight, 0 % by weight  $\leq$  Mn  $\leq$  1.0 % by weight, 0 % by weight  $\leq$  Si  $\leq$  0.5 % by weight and 0.5 % by weight  $\leq$  Cr  $\leq$  8 % by weight and/or 0.5 % by weight  $\leq$  Mo  $\leq$  8 % by weight, wherein (Mo+Cr)  $\leq$  8, rest iron and unavoidable impurities.
2. Sensor according to claim 1,  
characterised in that  
the magnetic field source (3) comprises a direct current (6) or an alternating current which generates a magnetic field.
3. Sensor according to claim 1 or 2,  
characterised in that  
the sensor further comprises at least one winding (6) wound around the flux conducting soft magnetic element (2).
4. Sensor according to any of claims 1 to 3,  
characterised in that  
the sensor (1) is a current sensor.
5. Sensor (1') according to claim 1,  
characterised in that  
the magnetic field source (3) comprises a permanent magnet (7) movable relative to the flux conducting soft magnetic element (2).

6. Sensor (1') according to claim 5,  
characterised in that  
the permanent magnet (7) is mounted on a rod.
7. Sensor (1') according to claim 5 or 6,  
characterised in that  
the permanent magnet (7) comprises a plurality of areas (8) with alternating  
directions of magnetisation (9).
8. Sensor (1') according to any of claims 1 and 5 to 7,  
characterised in that  
the sensor (1') is a position sensor.
9. Sensor (1) according to any of the preceding claims,  
characterised in that  
the flux conducting soft magnetic element (2) forms a magnetic circuit with at  
least one air gap.
10. Sensor (1') according to any of the preceding claims,  
characterised in that  
the flux conductor (2) has one or more slots, each of which provides an air gap  
(4).
11. Sensor (1, 1') according to any of the preceding claims,  
characterised by  
 $38 \% \text{ by weight} \leq \text{Ni} \leq 45 \% \text{ by weight}$ .
12. Sensor (1, 1') according to any of the preceding claims,  
characterised by  
 $1 \% \text{ by weight} \leq (\text{Cr}+\text{Mo}) \leq 8 \% \text{ by weight}$ .
13. Sensor (1; 1') according to any of the preceding claims,  
characterised by

0 % by weight  $\leq$  Co  $\leq$  0.5 % by weight.

14. Sensor (1; 1') according to any of claims 1 to 11,  
characterised in that  
the magnetic field sensor comprises a strip of amorphous soft magnetic material.
15. Sensor (1; 1') according to any of the preceding claims,  
characterised in that  
the magnetic field sensor (5) is a Hall probe.
16. Sensor (1; 1') according to any of the preceding claims,  
characterised in that  
two or three magnetic field sensors are provided.