Optical Position and Time Resolved Measurement of Magnetic Field Distribution in High Speed Metal Forming

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Abstract

In the area of the position and time resolved measurement of the magnetic field distribution in small gaps between workpieces and coils in high-speed sheet metal forming optical sensors are predestined to be integrated into the very small geometries of experimental setups.

Optical sensors for current measurement based on the magneto-optic Faraday effect are well known for a long time. This effect can also be used for the direct measurement of magnetic fields. For the use in electromagnetic high-speed metal forming applications, only very small field probes are probable. The measurement of axial symmetric fields can be achieved with two connected fibres with different Verdet constants. They solve the problem with the not given measurement value, which occurs by the use of only one fibre because of its closed integral domain. A continuous time signal of the magnetic field can be calculated for discrete regions.

Likewise, it is possible to employ miniature fibre-optic magnetic field point sensors for the field determination in the gap of an electromagnetic high-speed forming device. It is necessary to examine the influence on the polarisation state and the intensity of the light in a fibre. There are two different sensors shown in this paper. One is based on a piece of flint glass fibre spliced between two polarising fibres, and the other sensor arrangement consists of two glued SiO_2 *blocks.*

A workbench for assembling of fibre-optic sensors using the splice technology has been constructed and will be presented.

First trial measurements of the magnetic field, compared to the causing current, show the functionality of these kinds of optical sensors and are discussed under the aspect of optimisation.

Keywords:

Miniaturization, Probe, Optical Fibre Sensor

1 Introduction

The use of optical sensors is of high interest in the area of the position and time resolved measurement of the magnetic field distribution in small gaps between workpieces and coils in electromagnetic high-speed metal forming devices. Among the typical advantages, like an inherent potential separation, they offer the possibility of integration into places with very small geometric boundary conditions.

Electromagnetic high-speed metal forming, e.g. for the use in the automobile industry, is an excellent method for forming a lot of materials, like alloys, which cause problems in classic low speed processes. The principle of a sheet metal forming device consists of a large capacitor bank, which gets loaded to a voltage of between 5 kV and about 20 kV. The charged capacitors are connected by a high-speed switch to a flat coil with a small amount of windings. The resulting transient current in the work-coil has an amplitude of some 10 kA and induces eddy currents in the workpiece. The result of the interaction of these currents is a force which accelerates the workpiece extremely fast and forms it in some microseconds.

Although electromagnetic forming is widely used for cylindrical forming the mechanisms in high-speed sheet metal forming are not well investigated up to now. For modelling this process, it is desirable to get information about the position- and time resolved distribution of the magnetic field in the gap between the workpiece and the forming coil during the forming process. This gap is given by the insulation foil which is needed because of the very high electrical field strength between workpiece and coil. Because of the small gap and the high field strength the use of small potential free optical sensors is compulsory.

2 Current measurement by use of Faraday effect

Fibre optic current sensors are well known for a long time [1]. They use the magneto-optic Faraday effect, whose functional principle is illustrated in Figure 1.

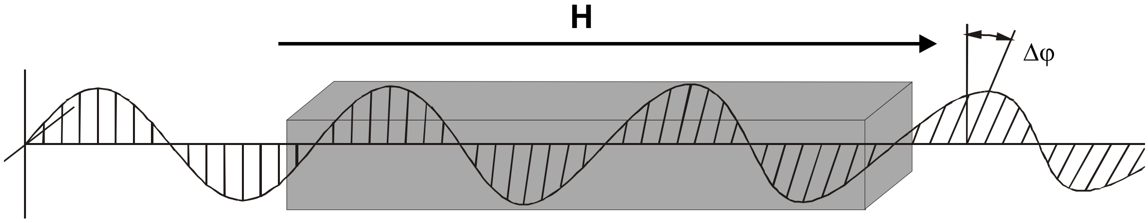

Figure 1: *Functional principle of Faraday effect*

An applied longitudinal magnetic field induces circular birefringence in the optical material. Therefore, a linear polarised light wave, propagating through the material, will receive a change in its polarisation angle $\Delta\varphi$ according to Equation 1, where k_V is called the Verdet constant.

$$\Delta\varphi = k_V \int_{c(\vec{s})} \vec{H} d\vec{s} \qquad (1)$$

The Verdet constant of typical standard fibres is about $4.6\cdot10^{-6}$ A^{-1}. Special fibres can reach much higher sensitivities (flint glass fibre at 820 nm: $2.1\cdot10^{-5}$ A^{-1}). If a closed loop with n windings is formed around a conductor the resulting angle is proportional to the current in the wire (Equation 2).

$$\Delta\varphi = k_V \cdot n \cdot I \qquad (2)$$

With an appropriate test setup and evaluation unit a potential free current sensor with high immunity against electromagnetic interference can be realised. Measurements of high impulse currents with such a device are shown in Figure 2.

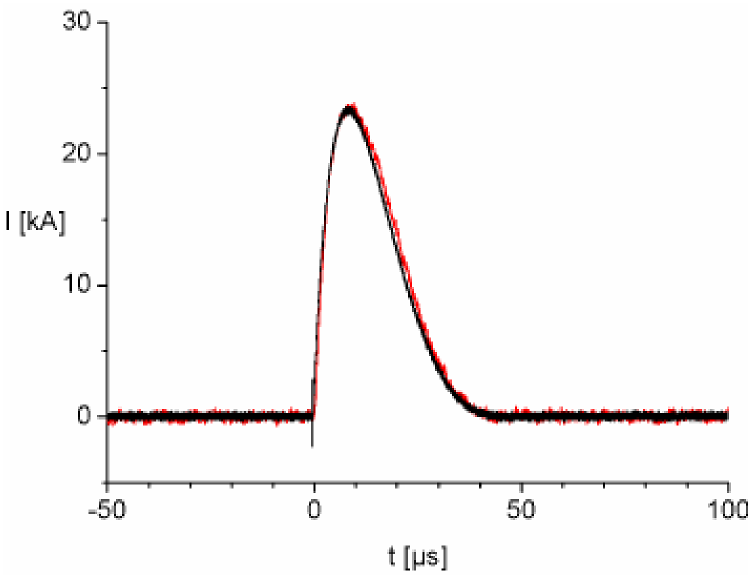

Figure 2: *Conventional and fibre-optic impulse current measurement at an optimised high current source [2]. The curves match within line width*

As an optimised shunt is used for comparison, there is no visible difference between the optical and the conventional measured signal.

3 Position resolved measurement of a symmetrical magnetic field with a distributed fibre sensor

Besides the standard application of current measurements the Faraday effect can also be used for direct measurements of magnetic fields. The time and position resolved field distribution between a workpiece and the windings of the coil of an electromagnetic high speed metal forming device is of special interest as it is the source for the resulting forces during the forming process. Regarding the electromagnetic and dimensional conditions at a typical setup (Figure 3) only non-conductive miniature field probes are applicable.

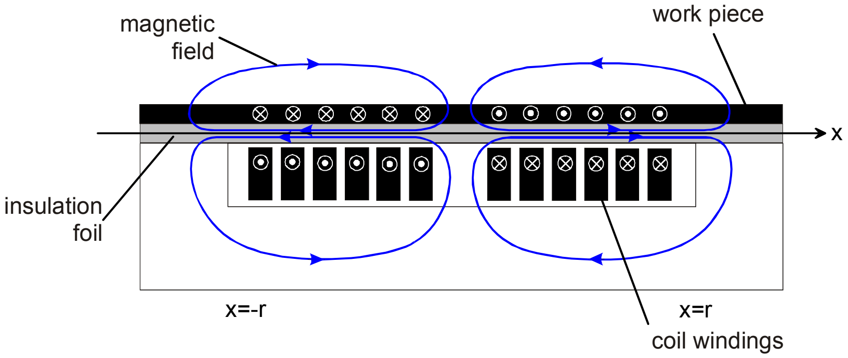

Figure 3: *Field configuration of a setup for electromagnetic high-speed metal forming. The insulation foil has a thickness of 600 µm, the radius r is 35 mm*

Measurements with only one fibre put into the gap would only give a time dependant integral value of the axial component of the magnetic field, but not a position resolved measurement. An axially symmetric magnetic field (Equation 3) would not even give a measurable value because of the compensating terms within the integral (Equation 4).

$$H_x(x) = -H_x(-x) \tag{3}$$

$$\Delta\varphi = \int_{-r}^{r} H_x(x)\cdot dx \cdot k_V = \int_{0}^{r} -H_x(x)\cdot dx\cdot k_V + \int_{0}^{r} H_x(x)\cdot dx \cdot k_V = 0 \tag{4}$$

Connecting two fibres with different Verdet constants (Figure 4) could solve this problem, so that the field's effect on one part of the sensor fibre is not fully compensated by the other part.

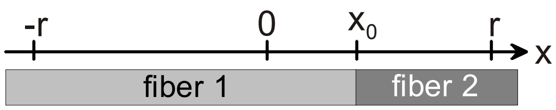

Figure 4: *Composite fibre sensor with different Verdet constants*

In a perfect symmetric magnetic field, where the axial component propagates along the fibre and is restricted to the area inside the coil (i.e.± r), it is possible to get a position and time resolved information about the magnetic field strength by pulling the fibre through the field along the x-axis (Equation 5).

$$\Delta\varphi = \int_{-r}^{x_0} H_x(x)\cdot dx \cdot k_{V1} + \int_{x_0}^{r} H_x(x)\cdot dx\cdot k_{V2} = \int_{x_0}^{r} H_x(x)\cdot dx \cdot (k_{V2} - k_{V1}) \tag{5}$$

The local resolution is determined by the distance between two measurement points as illustrated in Figure 5.

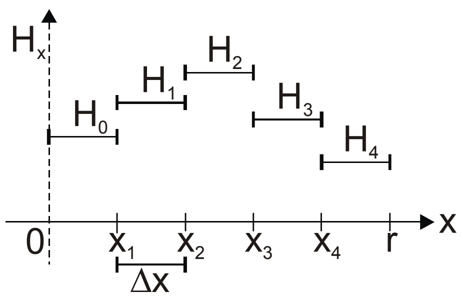

Figure 5: *Principle of field distribution with discrete values*

For a simple calculation of the respective fields, consecutive measurements beginning at the edge of the coil (here x_4) have to be carried out. The time and position resolved field distribution follows Equation 6.

$$\Delta\varphi = \int_{x_4}^{r} H_x(x)\cdot dx \cdot (k_{V2} - k_{V1}) = H_4 \cdot \Delta x \cdot (k_{V2} - k_{V1}) \Leftrightarrow H_4 = \frac{\Delta\varphi}{\Delta x \cdot (k_{V2} - k_{V1})}. \quad (6)$$

The values for the next step (here x_3) depend on the new measurement and the previously calculated field strengths (Equation 7).

$$\Delta\varphi = H_3 \cdot \Delta x \cdot (k_{V2} - k_{V1}) + H_4 \cdot \Delta x \cdot (k_{V2} - k_{V1}) \Leftrightarrow H_3 = \frac{\Delta\varphi}{\Delta x \cdot (k_{V2} - k_{V1})} - H_4. \quad (7)$$

So, a continuous time signal of the magnetic field can be calculated for discrete regions. In case of a not perfect axial symmetrical field this method would only give approximated values, thus a miniature magnetic field point sensor would be advantageous.

4 Miniature fibre-optic magnetic field point sensors

There are several optical point sensors suggested in the literature, but none of them is usable in the special case of field determination inside the small gap of an electromagnetic high-speed forming device because of their saturation field strength (about 20 Tesla have to be measured) or dimensions. Nevertheless, the functional principle keeps the same, similar to that of the current sensor. Linear polarised light is entering a sensitive fibre or crystal with a defined angle and is subject to circular birefringence. After passing through the optic material, the rotation of the polarisation angle is converted into a variation of the light's intensity.

The polarisation state in standard multimode fibres is affected by the magnetic field. As the magnetic field is not restricted to the area between the coil-windings and the workpiece, stray fields at the edge of the coil have to be taken into account as well. Hence, special precaution is necessary for the connection of the sensor itself with the light source and the photoreceiver. Preliminary investigations show that the polarisation state and the intensity of light is not affected by a magnetic field if a special polarising fibre is used. Another possibility is to use a depolarised light source and polarising surfaces at the sensor's boundaries.

The dimensions of the sensing fibre/crystal are of special interest as they determine the local resolution of the sensor on the one hand, and its implementability on the other. Microscope photos from two assembled sensors are shown in Figure. 6.

a)
b)

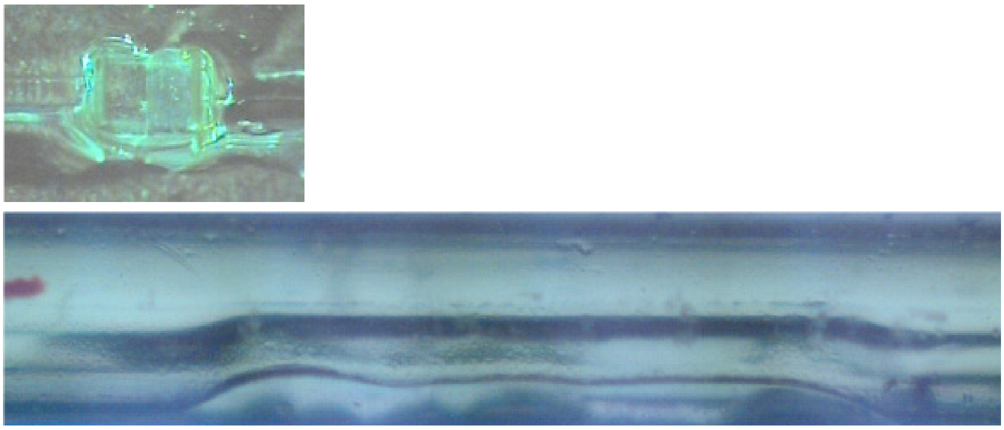

Figure 6: *Miniature magnetic field sensors. a) Multimode fibres (200/220 µm SiO_2) with glued crystals (1 mm × 500 µm SiO_2) with polarising surfaces. b) Polarising fibres (3M FS-PZ-4611) with spliced piece of flint glass fibre (HOYA LBF-850, 1 mm long) and protective cover*

One sensor consists of two crystal blocks with an edge length of 500 µm each. Both blocks have a polarising surface glued to a multimode fibre. The other sensor consists of a small piece of flint-glass fibre which is spliced between two polarising fibres.

5 Assembling of polarimetric fibre sensors

As the mode field diameter of a single mode fibre at 820 nm is about 6 µm, it is very difficult to connect two fibres with minimal loss. Only the use of splicing technology seems to succeed. If polarising or polarisation maintaining fibres are used they have to be spliced with defined angles in addition. Consequently, a workbench had to be constructed which makes it possible to build polarimetric fibre sensors with suitable effort (Figure 7).

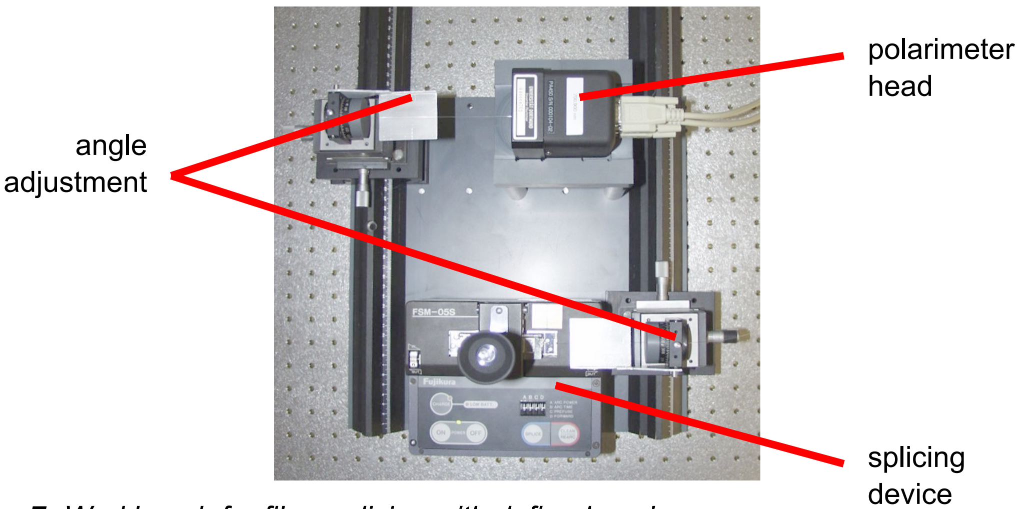

Figure 7: *Workbench for fibre splicing with defined angles*

A left and a right rail carry rotateable holding fixtures which guide the end of a fibre. The fibre is placed in front of a computer-controlled polarimeter. The holding fixture can be rotated until the desired orientation is indicated by the polarimeter. After that, the holding fixture is moved to the splicing device where the fibre end will be fixed. After translating the polarimeter, the same procedure is repeated for the other fibre end.

6 First field measurements

First trial measurements of the magnetic field have been carried out with the described flint glass fibre sensor at a device for electromagnetic high speed metal forming. The sensor has been placed in the gap between the coil and an alloyed workpiece. The recorded signals are presented in Figure 8.

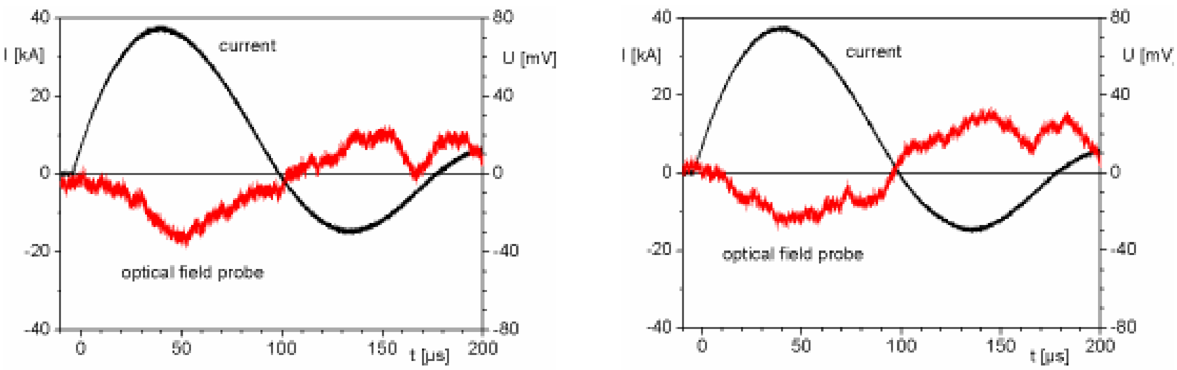

Figure 8: *Measurements of the magnetic field in the gap between a fixed workpiece and the coil of an electromagnetic high-speed metal forming device (Maxwell Magneform 7000) with the sensor from Figure 6b at position x = 20 mm*

Due to the high field strength the sensor could not be calibrated before, so only the measured voltages from the evaluation unit are given. The transient current, which is conducted through the coil, causes a magnetic field. Together with the induced eddy currents in the workpiece a resulting field configuration is generated as indicated in Figure 3. Hence, the pattern of the magnetic field signal does not have to be equal to the applied current which is shown in Figure 8, too. Since consecutive measurements show different signals the following reasons are taken under consideration: The field configuration might be very sensitive to small changes or mechanical coupling may disturb the sensor.

Restrictions to the sensor placement are given by the need to put a dielectric layer between the electrodes for electrical insulation and mechanical stability. An incorporated fibre cannot be moved unless there is a small gap with fluid or gas between the fibre's coating and the insulating foil. Another aspect is that fibre implementation has to be done with respect to vibration during metal forming. The fibre must not be exposed to strain or stress, as these components induce birefringence by their own. So an optimised mechanical setup is essential for further investigations with various optical sensors.

7 Conclusion

Miniaturised fibre-optic magnetic field probes are a promising technology for the experimental determination of the magnetic field in a 600 µm gap with an extremely high field strength. First measurements with a specially assembled sensor prove the principle functionality and show great potential for further research.

8 Acknowledgement

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References

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