The influence of assist gas on magnetic properties of electrotechnical steel sheets cut with laser

Dominika Gaworska-Koniaręk¹, Bronisław Szubzda¹, Wiesław Wilczyński², Jerzy Drosik³, Kazimierz Karas³
¹Electrotechnical Institute, Division of Electrotechnology and Materials Science, Wrocław, Poland, ²Electrotechnical Institute, Warsaw, Poland, ³ALSTOM Power Sp. z o.o. Wrocław Branch, Wrocław, Poland
gaworska@iel.wroc.pl

Abstract. The paper presents the influence of assist gas (air and nitrogen) during laser cutting on magnetization, magnetic permeability and loss characteristics of non-oriented electrical steels. The research was made on an non-oriented M330-50A grade electrical steels by means of single sheet tester. In order to enhance the effect of cutting and the same degradation zone on magnetic properties, strips with different width were achieved. Measurements results indicate that application of air as assist gas has more destructive effect on magnetic properties of electrical steels than nitrogen one.

1. Introduction
Electrotechnical steels – in relation to the rate of production – constitute the most important magnetically soft materials which are used in the production of magnetic cores of electric machines. In order to follow the market needs, the manufacturers of electric machines still look for the cheapest and quickest technologies of magnetic cores production. Increasingly, manufacturers resign from the mass production of machines and they produce them only to a special order as well as they adjust sizes and parameters to a specific order. Small and short series of production as well as a continuous improvement of machine constructions force manufacturers of machines to change production lines quickly and economically.

Nowadays, in the majority of electrotechnical industry factories which produce the magnetic circuits elements of electric machines, punching of sheets by means of punching dies on the fast-cutting presses have been prevailing for decades invariably (over 300 hits a minute). The process of punching is quick, while the time which is needed for its preparation is very long. A considerable cost and long time of making punching dies, the necessity of sharpening as well as a limited time of their existence have become, among others, the reason for searching other methods of cutting out shapes, for example, by means of laser. In spite of the fact that the process of cutting out by means of laser is more time-consuming than the mechanical punching, it has a number of advantages which increasingly decide about its application. Cutting by means of laser opens up possibilities of making changes in forms and sizes of shapes without bearing additional costs. This requires only the change in the computer program which controls the laser work. Moreover, considering a non-contact cutting effect, in this process the burr edge effect is avoided, which, in turn, can lead to the short-circuit between the laminated sheets and in this way can become a reason of the increase of losses from eddy
currents. Nevertheless, the performance of the impulse laser beam with a big power density in a short
time, which causes melting and partial vaporization of the material, can change a microstructure of the
electrotechnical steel sheet along the cutting line. Laser cutting out of steel is commonly used in the
industry but its influence on magnetic properties of electrotechnical steel sheets is still not recognized
well in spite of many years’ studies.

The results presented in the literature are often discrepant and to a large extent they depend upon
the employed type of electrotechnical steel, sample sizes, laser beam power, laser type, etc. For
instance, in [1], it was shown that laser cutting of non-oriented electrotechnical steels leads to the
increase in total energy loss in the range 3 to 17 %. However, this increase is lower than what we
observe after mechanical punching. The research by Lanott [2] conducted on 3% Si grain-oriented
electrotechnical steels also confirmed the advantage of laser cutting over mechanical cutting as regards
the total energy loss. On the other hand, Belhadj in [3] proved that laser cutting in the assisting
atmosphere of oxygen deteriorates the magnetic properties of electrotechnical steels to a larger extent
than punching. It particularly has an impact on the increase of losses as well as the decrease of
magnetic permeability. In the case of the coercion value, depending on the selected cutting parameters
and the type of an electrotechnical steels, the result was the coercion decrease or increase in relation to
the punched samples. Dupre in [4] showed that laser cutting causes the greatest increase of loss from
hysteresis in electrotechnical steels in comparison to punching.

All of the above mentioned publications investigate the influence of different parameters of the
laser cutting process on the magnetic properties of electrotechnical steels, however, none of them takes
into account the influence of the associated gas which is employed during this process and whose type
and pressure can influence the final magnetic properties of the shape. The most commonly
encountered results in the literature of the subject are those for laser cutting in the associated
atmosphere of nitrogen, and very rarely of oxygen [3]. However, there are no publications known to
the authors, which take into account the influence of the associated gas employed during this process
whose composition and type can affect the final magnetic properties of the shape. This paper, in which
we present the influence of the two most commonly used associated atmospheres – air and nitrogen on
the magnetic properties of electrotechnical laser cut steels, partly fills in this gap.

2. Magnetic measurements

The aim of the magnetic investigations was to determine the influence of cutting and the type of the
employed associated gas on the magnetic properties of electrotechnical steels – the magnetization
curve, magnetic permeability and specific total energy loss. The measurements were executed by
means of the computerized measuring position MAG-RJJ-3.0 with the usage of the Single Sheet
Tester (SST), according to the norm PN-EN 10280:2003 [5] on two sets of M330-50A grade
electrotechnical steel samples cut out by means of laser in two different associated atmospheres. These
were: 1) laser cut out samples in the atmosphere of the air, 2) laser cut out samples in the protective
atmosphere of nitrogen. The samples were magnetized perpendicular to the direction of rolling. The
set consisted of samples with the following dimensions:

- 500x500 mm sheet – two cutting edges,
- 500x500 mm sheet cut into two equal parts perpendicular to the direction of rolling
  (dimension 250x500 mm) – four cutting edges,
- 500x500 mm sheet cut into four equal parts perpendicular to the direction of rolling
  (dimension 125x500 mm) – eight cutting edges,
- 500x500 mm sheet cut into eight equal parts perpendicular to the direction of rolling
  (dimension circa 62.5x500 mm) – 16 cutting edges,
- 500x500 mm sheet cut into 16 equal parts perpendicular to the direction of rolling
  (dimension circa 31.25x500 mm) – 32 cutting edges,

500x500 mm sheets constituted the so called reference sample. Along with the sheet dimension getting
smaller, there appears the increase of the influence of the deformed and, if necessary, oxidized cutting
zone on the magnetic properties of the material. In the case of 500x500 mm sheets, on account of a big
distance of the cutting edges and at the same time an insignificant part of the deformed zone in the total mass and volume of the sample, it can be assumed that they are deprived of stresses connected with the sample preparation. The appearance of lateral surfaces of M330-50A grade steel cut by means of the punching die and laser is presented in Fig. 1. The magnetization curve, magnetic permeability and specific total energy loss were measured. The chosen measurements results are presented in Table 1. The course of magnetization curves of the examined samples was shown in Fig. 2. Relative changes of maximum magnetic permeability ($\mu_{\text{max}}$) and total energy loss ($P_c$) are presented in Figs. 3a and 3b. For comparison purposes, the diagrams also present the results obtained for 16 punched strips of M330-50A grade steel size 31.25x500 mm.

### Table 1. Chosen magnetic properties of laser cut out sheets in the atmosphere of nitrogen and air

| Sample             | Width of strip [mm] | $B_m$ [T] for 100 A/m | $B_m$ [T] for 500 A/m | $B_m$ [T] for 1000 A/m | $\mu_{\text{max}}$ [-] | $H_{\mu_{\text{max}}}$ [A/m] | $P_c$ [W/kg] |
|--------------------|---------------------|-----------------------|-----------------------|------------------------|------------------------|-----------------------------|--------------|
| Reference          | 500                 | 0.82                  | 1.40                  | 1.46                   | 6548                   | 100                         | 1.36         | 3.19         |
| Laser cut - nitrogen atmosphere | 250                 | 0.79                  | 1.40                  | 1.46                   | 6318                   | 100                         | 1.38         | 3.21         |
|                    | 125                 | 0.74                  | 1.40                  | 1.46                   | 5886                   | 100                         | 1.42         | 3.30         |
|                    | 62.5                | 0.62                  | 1.39                  | 1.45                   | 5108                   | 150                         | 1.50         | 3.42         |
|                    | 31.25               | 0.40                  | 1.37                  | 1.45                   | 3713                   | 150                         | 1.73         | 3.72         |
| Laser cut - air atmosphere | 250                 | 0.79                  | 1.40                  | 1.46                   | 6242                   | 100                         | 1.38         | 3.21         |
|                    | 125                 | 0.70                  | 1.39                  | 1.46                   | 5572                   | 100                         | 1.44         | 3.33         |
|                    | 62.5                | 0.54                  | 1.38                  | 1.46                   | 4683                   | 150                         | 1.57         | 3.59         |
|                    | 31.25               | 0.33                  | 1.35                  | 1.44                   | 3258                   | 200                         | 1.83         | 3.83         |
| Punched            | 31.25               | 0.70                  | 1.35                  | 1.44                   | 5569                   | 100                         | 1.48         | 3.44         |

Fig. 1. Sheet edges after cutting by means of the punching die and laser

Fig. 2. The magnetization curves for different strip widths cut out with laser in the nitrogen atmosphere, with laser in the air atmosphere
Thermally degraded areas of lateral surfaces of laser cut out sheets prove the suspicion as to a possible influence of the chemical composition of the protective gas atmosphere in which this process takes place on the level of degradation, which can be observed in Fig. 1. Particularly, by the application of the oxidized atmosphere – air, we can expect foreign layers on surfaces which appear as a result of high energy laser cutting.

![Graph](image)

Fig. 3. A relative change of maximum magnetic permeability (a) and total energy loss $\Delta P_c$ for $B_m=1.5$ T (b), for different strip widths cut out with laser in the nitrogen atmosphere, with laser in the air atmosphere and with a punching die

3. X-ray examinations

X-ray measurements were carried out on DRON-2 prom. Co/Fe diffractometer on samples of laminated sheets stuck together and placed in a frontal position. X-ray diffraction patterns of samples are presented cumulatively in Fig. 4.

Barium sulfate $\text{BaSO}_4$ which was identified in diffraction patterns, comes from the superficial insulating layer of electrotechnical steels. Additionally, in the sample, which was cut in the protective atmosphere of the air, the presence of iron oxides was noticed. As far as magnetic properties are concerned, a particularly unfavourable phenomenon is the formation of magnetite $\text{Fe}_3\text{O}_4$, which shows hard magnetic properties (coercion $H_c$ of the order of some kA/m).
Samples cut with laser in the air atmosphere also show a smaller size of crystallites (~ 52 nm) than steels cut in the nitrogen atmosphere (~ 55 nm). This can happen as a result of greater structure defecting. Dimensions of the crystalline cell were not changed.

4. Research results analysis
The research results show that the strips widths, which are part of the examined sample, i.e. the increase of the degraded zone share as a result of cutting/punching, have an influence on the electrical steels magnetic properties. The increase of the degraded zone share causes the flattening of magnetization characteristics of the examined samples – Fig. 2 and at the same time, a decrease of magnetic permeability – Fig. 3a. This effect is particularly seen for the narrowest samples.

The width of component strips and at the same time, the cutting zone share in the sample volume has also an influence on the total specific loss of the examined electrotechnical sheets – Fig. 3b. Total energy losses after laser cutting in the air atmosphere increased by 35% for 1.0 T induction and by circa 20% for 1.5 T induction. The application of the atmosphere of nitrogen at cutting limited the increase of total energy losses up to 27% for 1.0 T induction and 17% for 1.5 T induction. When using punching the increase of losses is much smaller and is circa 9% for 1.0 T induction and circa 5% for 1.5 T induction.

The reasons for deterioration of magnetic properties are compressive stresses which appear during cutting/punching and which result in changing the magnetic structure of the material and the increase of 90° domain volume at the cost of 180° domains [6]. Therefore, the process of magnetization changing requires the use of greater external magnetizing field in order to change the domain structure in the stress area along the lines of punching. This is the reason of the increase of hysteresis losses and anomalous losses [6]. Movements of domain wall take place at the lower inductions (a steep part of the magnetic curve) and in this range they are mainly responsible for the hysteresis loss. During the magnetization process when inductions are higher, the processes which dominate are connected with domain magnetization vector rotations and their influence on hysteresis losses is smaller. Thus, a greater percentage-wise increase of a total specific loss can be seen for the lower values of induction. A big increase of hysteresis loss after laser cutting in comparison to the increase of loss after punching shows that during this process bigger stresses and/or in a bigger sample volume than in the case of punched samples are introduced into the material.

After punching, as a result of plastic deformations the zone of the deformed material is created (the zone width measured from the edge is from 0.1 mm for sharp blades, up to 0.23 mm for the blunt ones [7]) as well as the stressed zone in which there are no visible grain strains. On the other hand, after
laser cutting the shrinkage of the material appears as a result of rapid heating at first and then equally fast cooling by means of the protective gas or air flux. An impulse laser beam which acts within a short time with a great power density produces a very high unsteady gradient temperature field along the cutting line. A very quick heating makes the material boil, which is immediately cooled with a high speed by means of the associated gas which blows out a liquid metal and its vapours from the gap. Within this layer at such a high temperature dislocations of atoms take place. In the grains along the cutting line, displacement of atoms may cause edge dislocations to climb; whereas, on the grain boundaries it may cause the slipping of one grain after the other. It may even lead to the creation of micro-cracks. These phenomena can become the reason of a significant increase of dislocations and stresses at the edge of the material, decrease of crystallites, as a result of which the magnetic properties may deteriorate [3]. The total width of deformed and stressed zones in the case of punching as well as in the case of cutting out is much wider and makes the so called slightly magnetic zone. For the non-oriented sheet it is circa 0.6 mm after punching [8,9] and up to 6.0 mm after laser cutting [10].

In the case of laser cut electrotechnical steels in the air atmosphere, iron oxide ($\text{Fe}_3\text{O}_4$) – magnetite which is created as a result of air cooling additionally hinders the process of magnetization; the presence of magnetite is proved by the conducted X-ray examinations. As it is a material magnetically hard, in order to change its domain structure we need a greater energy of the external magnetic field the consequence of which is the flattening of magnetization characteristics, decrease of magnetic permeability and increase of hysteresis and anomalous losses. Moreover, foreign inclusions such as oxides appearing on the cutting edges can act as an pinning centres which inhibit the movement of domain walls and additionally increase the coercion of material and hysteresis loss.

5. Summary
The executed research explicitly indicate that the participation of the zone degraded as a result of cutting of the examined electrotechnical steels measured with the number of cutting edges, has a significant influence on magnetic properties of electrotechnical steels. Decreasing the widths of strips included in the examined sample and at the same time increasing the participation of degraded zone causes flattening of the magnetization curves as well as the decrease of maximum magnetic permeability. We can also observe the increase of hysteresis and additional losses.

A negative influence of cutting/punching on magnetic properties of electrotechnical steels is more visible in the case of laser cut samples than in the case of punched samples. Moreover, we can see the influence of the applied assist atmosphere during laser cutting on the level of deterioration of magnetic properties of electrotechnical steels – the employment of the air atmosphere has a more unfavourable impact on the steel magnetic properties than the nitrogen atmosphere. Most probably, this results from the creation of iron oxides on the cutting edges, which can act as an anchor centres inhibiting the movement of domain walls. Moreover, iron oxide $\text{Fe}_3\text{O}_4$ shows hard magnetic properties, which additionally increases the material coercion and hysteresis losses.

References
[1] Dickmann K., Influence of laser cutting process on the magnetic properties of electrical sheets, Anales de Fisica B, 86, 82, 1990.
[2] Lanotte L., Luponio C., De Iorio I., Tagliaferri V., Tammaro G, Effect of laser cutting on magnetic properties of grain oriented Fe-Si ribbons, Mater. Sci. Technol., 8, 252-256, 1998.
[3] Belhaldj A., Baudouin P., Breban F., Deffontaine A., Dewulf M., Houbaert Y., Effect of laser cutting on microstructure and on magnetic properties of grain non-oriented electrical steels, J. Magn. Magn. Mater. 256, 20 -31, 2003.
[4] Dupre L.R., Van Kerr R., Melkebeek J.A.A, A study of the influence of laser cutting and punching on the electromagnetic behaviour of electrical steel sheets using a combined finite element-dynamic Preisach model., Fourth International Workshop on Electric and Magnetic Fields, Marseille, France, 12-15 May, 1995 - , 1998.
[5] PN-EN 10280:2003 Magnetic materials – Measurement methods of sheets and electrotechnical
tapes magnetic properties by means of the device for single sheet examination.

[6] LoBue M., Sasso C., Basso V., Fiorillo F., Bertotti G., Power losses and magnetization process in Fe -Si non-oriented steels under tensile and compressive stress, J. Magn. Magn. Mater. 215 - 216, 124-126, 2000.

[7] Matheisel Z., Cold-rolled electrotechnical sheets, WNT Warszawa, 1973.

[8] Wilczyński W.: The influence of technology on magnetic properties of electric machine cores, Prace Instytutu Elektrotechniki, zeszyt 215/2003

[9] Wilczyński W., Szubzda B., Talik S., Lipiec W., Aspects of the punching and laser cutting effect on the power losses and flux density distribution in electrical steel, Proceedings of SMM16, 499, Düsseldorf 2003.

[10] Loisos G., Moses A.J., Effect of mechanical and Nd:YAG laser cutting on magnetic flux distribution near the cut edge of non-oriented steels, Journal of materials processing technology, 161, 151-155, 2003.